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Discussed is an instructional approach, "concept-distillation," which involves experiences, games, and puzzles that have the "distilled essence" of the basic concepts of the physical sciences. This approach is designed to impart a vivid and dramatic meaning and structure of the sciences for transfer in scientific thinking. The materials consist of a series of five booklets of text and exercises (total class time, 10 hours). Central to four of these is the invariance principle of the odd-even sequence of whole numbers. One booklet introduces the principles of physical optics, while others involve the invariance principle in (1) center of gravity of rigid bodies, (2) laws of moments of levers, (3) gravitational potential energy, and (4) Archimedes' Principle. In the summer of 1967, experimental testing of the program was conducted, using students studying Introductory Physical Science (IPS) and the Earth Science Curriculum Project (ESCP) materials as the comparison groups. The conclusion drawn was that this program is capable of producing changes in attitudes about science and problem solving. This report contains the conceptual, theoretical, organizational, administrative, implementative, and evaluative aspects of the program while the actual materials and appendixes are contained in another volume. (DH)

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FINAL REPORT

Project No. S-090
Contract No. OE 6-10-026

U.S. DEPARTMENT OF HEALTH, EDUCATION & WELFARE
OFFICE OF EDUCATION

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THE CONSERVATION OF ENERGY CONCEPT IN NINTH GRADE GENERAL SCIENCE

February 1968

U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE

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Final Report

Project No. S-090
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THE CONSERVATION OF ENERGY CONCEPT IN NINTH GRADE GENERAL SCIENCE

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Stanford, California

February 1968

The research reported herein was performed pursuant to a contract with the Office of Education, U.S. Department of Health, Education, and Welfare. Contractors undertaking such projects under Government sponsorship are encouraged to express freely their professional judgment in the conduct of the project. Points of view or opinions do not, therefore, necessarily represent official Office of Education position or policy.

U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE

Office of Education
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PREFACE

The request for a grant from the U.S. Office of Education to explore the use of puzzle and game situations to illustrate certain principles of physics was conceived by William B. Shockley, a professor in the Stanford School of Engineering. His interest grew out of the inability of high school students to "think through" simple problems that should have been apparent if logical reasoning were used. The idea developed that if a system of logical thinking could be learned with materials of high interest and essentially divorced from subject matter content and then later, using the same logical processes with specific subject matters, the students might be better prepared to solve these science problems. This, of course, means that the "puzzle situations" involve the thinking attributes to be found when working in a science context.

A planning grant was requested and granted from the U.S. Office of Education in 1964 to explore the problem and to test its feasibility. The results of this study seemed promising and a further study with more refined materials and under better controlled research conditions was envisaged. A proposal was prepared and submitted through the School of Education at Stanford University to USOE. The beginning date of the new study was set for May 1965. A research staff was tentatively employed, arrangements were made with public schools, and a writing conference was planned for the summer of 1965. Although the proposal was approved by USOE and Stanford University to the satisfaction of each, the contract was not executed until November 1965. This meant that the original writing and planning conferences and the experimental tryout of materials had to be postponed. Certain adjustments were made making it possible to begin the education of teachers in the program during the spring months of 1966 and permitting the first school experimentation during the summer of 1966.

In acknowledgment the investigators wish to express their deep appreciation and thanks to the following schools for their participation in the Stanford-Shockley Science Education Project during 1966-1967: Ray Lyman Wilbur, David Starr Jordan, and Lewis M. Terman Junior High Schools (Palo Alto Unified School District, Palo Alto); Carlmont and San Carlos High Schools (Sequoia Unified School District, Redwood City); and Andrew Hill High School (East Side School District, San Jose). Administrative support from John Martin, Assistant Superintendent, Palo Alto, and Dale Nelson, Science Coordinator, San Jose, is gratefully acknowledged. Special thanks are extended to the following science teachers who taught the Shockley materials: Ray Rayner, Donald McRae, Mrs. Ruth Hainsworth, Robert Alvares, Michael Donovan, Jack Flesher, and Fred Taylor, all of Palo Alto; Orrin Cross and Donald Guilo of San Carlos; Jerry Rollins of Carlmont; and Jack Grube, Stewart Eastman, and Charles Smith of Andrew Hill.

GLOSSARY OF SPECIAL TERMS

	Where First Introduced or Defined
acor (key attribute - comparison operation - orderly relationship)	Sec. 1E, p. 25; Sec. 2C, p. 37
articulated science teaching	Sec. 1E, p. 21
balanced emphasis	Sec. 1E, p. 21
conaddians	Sec. 2C, p. 42
concept distillation	Summary, p. 1; Chap. 1. p. 6ff
creative search pattern (CSP)	Sec. 1E, p. 25; Chap. 2
inward-directed analysis	Sec. 1A, p. 6
postulate-proof-theorem (PPT)	Sec. 1E, p. 25; Sec. 2C, p. 40
qualified law form (QLF)	Sec. 1E, p. 25; Sec. 2C, p. 37
search thinking tools (STT) (see science thinking diagram)	
science thinking diagram	Sec. 1E, p. 25; Fig. 2-1, p. 38

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SUMMARY OF THE CONCEPT-DISTILLATION APPROACH TO TEACHING THE PRINCIPLE OF CONSERVATION OF ENERGY

This report is concerned with a new approach to teaching the basic laws of science with particular applicability to conservation and invariance laws in general, and to conservation of energy in particular. It is also concerned with the development of thinking attitudes and thinking tools and with an attempt to determine the degree to which imparting these tools enables better rational reasoning to be carried out in related areas. Developing the attitude that knowledge is power is an important objective of the program.

A. The Concept-Distillation Approach

Concept distillation describes an approach which the principal investigator first formalized in 1963 and which is the basic approach of the project.* This approach consists of giving the student experience with selected games and puzzles that have been chosen and invented so as to be soluble with the aid of invariance or conservation principles like those in physical science. In effect, these games and puzzles contain the distilled essence of the concepts involved in the basic physical laws. This approach can be described as imparting vivid dramatized patterns of logical structures for transfer in scientific thinking.

Instructional materials have been prepared in the form of booklets, which are discussed in Chapter 2 and are available in the appendix. Briefly, there are five booklets of text and exercises (requiring a total of about 10 class hours for all five) which present the distilled essence of invariance and conservation principles. Specially developed in four of these is what is probably the most elementary invariance principle of mathematical science, namely, the odd-even sequence of whole numbers that in sophisticated form underlies expansion of algebraic determinants, quantum statistics, etc. One booklet introduces physical optics principles while relating odd and even multiple reflections in mirrors to right- or left-handedness of images. Additional parallel booklets transfer invariance concepts to center of gravity of rigid bodies, laws of moments of levers, gravitational potential energy, Archimedes' principle, and a survey of energy in general.

Teachers were trained for the program during a spring seminar and also during a summer booklet-preparation program, both in 1966.

---

*The term "concept distillation" was conceived after the project was begun and appears for the first time in this final report. Note also that for convenience the formal project title, "The Conservation of Energy Concept in Ninth Grade General Science," has been variously referred to throughout this report as the "Shockley Science Education Project," the "Shockley-Stanford Project," and the "Shockley program."

Evidence has been obtained, largely of an anecdotal nature, showing that experience in the games and puzzles enables a student to make a transfer so as to discover for himself some of the invariance principles in science. In particular, a number of students have been observed who discovered the principle of conservation of energy for the limited case of potential energy as exchanged by lever systems. (One of these cases is described in Section 1E of the report.)

B. Thinking About Thinking

The teaching approach also involves the use of diagrams that illustrate certain basic features of the creative process of finding new ideas or relationships. Attention is focused upon the thinking processes in the teaching in a form of inward-directed analysis. Two themes involved are "Knowledge is Power" and "Thinking about Thinking Improves Thinking."

These features are brought out with the aid of four strongly emphasized thinking tools that are combined in a science thinking diagram. This diagram (the Creative Search Pattern, CSP) is discussed in detail in Sections 1E and 2C.

An important aspect of this teaching is that creative search frequently involves "bum hunches" which lead to increased familiarity with the problem but which at the same time may result in failure to achieve the desired answer. The student learns from this that mistakes are to be expected and that one may learn and make progress even though a number of failures occur.

The creative search pattern emphasizes some of the random features involved in creating new orderly structures. The new orderly structures are logical relationships that are described in a special terminology and are given the name "acor" patterns. The acor concept is described fully in Section 1E.

The orderly relationship, which represents the "or" of the word acor, is frequently presented as a qualified law form (QLF) which shows the limitations that ordinarily prevail for even the most reliable and extensive of laws of nature. (The QLF is also discussed in Section 1E.)

The inward-directed analysis associated with thinking about thinking also focuses on a set of search thinking tools. This set consists of the following:

1. Action
2. Try simplest cases
3. Pencil and paper
4. Symbols and diagrams
5. One-to-one correspondences
6. Idealized limiting cases
7. Conceptual experiments

Most important among the search thinking tools is the first; it indicates that any action which furnishes personal contact with the difficulties of the problem will help fix relevant features of it in one's mind.

C. Testing for Transfer and Changes in Attitude

Part of the program consisted of attempts to measure the degree to which experience in the rational reasoning processes involved in the concept-distillation approach and the inward-directed analysis of thinking about thinking, might affect ability to deal with problems in other areas. One difficulty in such a study is the lack of a set of adequate tests to determine ability to carry out the problem-solving type of creative thinking involved in this program. Some conventional tests are related to these abilities, such as the Raven Progressive Matrices Test and the Differential Aptitude Test for Abstract Reasoning. Both these tests are relatively simple, however, and do not involve the phrasing of problems in the same way as occurs in actual reasoning problems in science.

An attempt was made to develop new tests, known as Rational Reasoning Tests. (See Section 4A for details.) These tests involved novel features based on experience with teaching the program. The tests in general were conducted at three levels: the first determined whether or not the student was able to solve the problem given no hints; in the second level the student was given a hint which would focus on a key attribute of the problem so that it would be more likely for him to transfer knowledge about similar problems to help solve this problem; in the third level he was given the answer to the problem and a way of thinking about it, and the questions were directed toward whether he was able to understand and to apply the knowledge that had been given to him.

The performance of students in the concept-distillation program, referred to as the Shockley program, was compared with students in other programs during the school year and during the summer in a meticulously planned controlled experiment.

D. Results

The first test of the Shockley program was conducted in the Palo Alto Unified School District during the second semester of the academic year, 1966-67. During the first semester of that year the program was given a preliminary test whose purpose was to try out the materials used, develop the skills of the teachers, and test the evaluation instruments. At the beginning of the second semester, ten classes were assigned to the Shockley program and ten remained in their regular programs (the students had not been assigned randomly to the classes). The classes in which the program was used were those whose teachers had worked with the program in the preceding semester. The "control" classes were matched to these classes on the basis of the lanes to which they had been assigned.

At the end of the program treatment period, all classes were given the Rational Reasoning Test, Form Z, the Standard Progressive Matrices Test, the Nature of Science Test, and the Problem-Solving Inventory. Statistically significant differences were found on these measures favoring the experimental classes. However, these results were not taken as conclusive since the method of assigning students to classes and the selection of experimental classes may have biased the results.

In the summer of 1967 an experimental test of the Shockley program was conducted with as rigorous controls as could be mounted. Junior high school students were notified in the spring that three science programs would be offered during summer school: the Shockley program, an Introduction to Physical Science program, and the Earth Sciences Curriculum Project program. They were told that they could sign up for science classes but would be assigned to one of the programs. The 101 children who signed up for the program were randomly assigned to one of the three programs.

The classes in each of these programs were taught by experienced teachers who were familiar with the materials of the program and who were enthusiastic about teaching that program. The classes were conducted over a six week period for four hours a day. At the beginning and the end of the program the students took the following tests: the Progressive Matrices Test, Rational Reasoning Test, Form Z, the Nature of Science Test, the Problem-Solving Inventory. In addition, at the end of the program they also took the Abstract Reasoning Test of the Differential Aptitude Test Battery, and the tests used in the Introduction to Physical Science program, the Earth Sciences Curriculum Project program, and the Biological Sciences Curriculum Project program.

The Shockley classes were significantly superior to the other classes on the first part of the Rational Reasoning Test, the Nature of Science Test, and the Problem-Solving Inventory. The science achievement measures favored the classes which took the program for which a particular measure was the criterion test. No marked changes in intellectual aptitude scores appeared in any of the classes.

It was concluded that the Shockley program is most likely to produce changes in attitudes about science and problem solving. Gains in problem-solving skills occur as the result of the Shockley program. However, since the measure of the latter has not as yet been demonstrated to be related to general problem-solving skills, the estimate of the amount of development of problem-solving skill must necessarily be conservative. Changes in skill and attitude related to problem solving do occur as a result of the Shockley program, but neither their generality nor their stability can be estimated from the evaluations conducted during this project.

E. Recommendations

The investigators on this project have the following recommendations to make regarding further research on the subject of learning to reason in science courses. These recommendations are treated in greater detail in Chapter 6, although not necessarily in this order.

1. Tests on rational reasoning should be developed that will assess the student's levels of insight into the process.

2. A reliable means is needed for assessing teacher competence in, and attitude toward, rational reasoning processes.

3. Teacher education in the processes of logical reasoning, especially as it relates to the behavior of teachers in teaching toward specified goals, is an area that requires further study.

4. The effect of small group interaction vs. individual study on improving rational reasoning processes should be explored.

5. The approximate length of time needed by students to typically reach a level of proficiency in logical reasoning needs further study, as well as the effect of high reasoning competence in science upon thinking in other subject fields.

6. The effect of the student's familiarity with relevant science phenomena upon acquiring skill in logical reasoning should be of interest.

7. Particularly fruitful might be a study of the ability of students to transfer the skills of rational reasoning learned in a puzzle context to a natural science context.

Chapter 1

HISTORY OF THE DEVELOPMENT OF THE CONCEPT-DISTILLATION APPROACH

A. Introduction

The approach on which this study is based may be summarized as "imparting dramatized vivid patterns of logical structures comprising invariance principles and transferring these to the invariance principles and conservation laws of physical science." The particular vivid patterns selected and invented for the study are presented in the form of games and puzzles that are characterized by principles of invariance and conservation like those in the physical sciences. In effect, the examples contain the distilled essence of the logical relationships contained in the more complex laws of science. This teaching approach to scientific thinking may be appropriately called concept distillation.

The concept-distillation teaching approach also furnishes a basis for inward-directed analysis[*] on the part of teacher and student that emphasizes two general principles: "Knowledge is power" and "Thinking about thinking improves thinking."

The development and intermixing of these ideas and their relationship to the project are described in historical perspective in Sections B through E of this chapter. These sections are largely condensations of previous publications and reports over a 4 year period. A concluding section is primarily anecdotal.

B. National Academy of Sciences Meeting, 1963

The basic ideas for this study were first published by Dr. Shockley as an abstract[†] for a paper presented at the spring 1963 meeting of the National Academy of Sciences. As part of his presentation, Dr. Shockley had several high school students describe their experiences, possibly the only occasion when teenagers have spoken at a meeting of the Academy. In the abstract, which is repeated below, it may be noted that certain phrasing was used that has been improved by subsequent experience (e.g., the words "progress" and "provided" have been changed):

PROPOSED IMPORTANT MENTAL TOOLS FOR SCIENTIFIC THINKING AT THE HIGH SCHOOL LEVEL

> Some experimentation during the Ohio "Project: Honoring the Science Scholar" suggests that the basic logical structure of a quantitative law of nature and its limits can be focused in the

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[*] See "introspective analysis" as discussed in pages 108 and 125 of William Shockley and Walter A. Gong, Mechanics, Charles E. Merrill Books, Inc., Columbus, Ohio, Merrill Physical Science Series, 1966.

[†] Science, 140, 1963, p. 384.

minds of students through puzzles having solutions based on unifying principles. For example, the Koenigsberg bridge problem has a law: It is *always true* that a land area with an odd number of bridges is a path terminus *no matter what* the numbers of bridges or land areas *provided that* no boats are used. Individuals of high school to post-doctoral level usually solve such problems by following the course (described for example in Hadamard, "Psychology of Inventions in the Mathematical Field") of acquiring *familiarity* with the phenomena, obtaining a *hunch* about the answer or law involved, and finally achieving *progress* by detailed analysis. Preliminary teaching experiments indicate that the logical structure of laws and methods of finding them can be learned and fixed in mind with aid of the italicized phrases, and that these concepts are probably the most important tools for scientific thinking that can be developed in high school. It is proposed that the next most important mental tool is facility in translating concept of quantitative reality into algebraic symbol and back again. An additional viewpoint of imporance is that the practice of science is an art; and personal predilection, rather than quantitative thinking, usually determines whether a problem calls for paper and pencil, experimental apparatus, reference to publications, or inquiry to a well-informed source.

C. The 1964 "Wilbur" Experiment

In 1964 a science thinking experiment was carried out at Ray Lyman Wilbur Junior High School in Palo Alto, California. The general philosophy of this experiment was presented by Professors Shockley and McDonald. Their report* included three of the four basic thinking tools which are discussed more fully in Chapters 2 and 3. The following two topics, Rationale and Methodology, are excerpted from that report.

Rationale

> The purpose of the studies reported here was to test the effectiveness of a way of thinking about problems and to test the effects of introducing junior high school students to the logic of scientific thinking.
>
> The search for general thinking tools is recurrent in the history of mankind. The object of this search has been to find general ways of thinking that enable man to solve many different kinds of problems, to generate ideas as diverse as poetry and scientific theory. The search has usually rested on a theory of mind or a theory of thinking. But even as anti-mentalist a philosopher as John Dewey wrote a book on thinking.

---

*William Shockley and Frederick J. McDonald, "Teaching Scientific Thinking at the High School Level," Final Report on Contract OE 4-10-216, Project S-090, School of Engineering and School of Education, Stanford University, Stanford, Calif., October 1964.

The recent history of education has revived interest in cognition. Bruner's speculation and research on such processes as discovery, intuitive and analytic thinking; the work of Torrance on creative thinking and that of Suchman on critical inquiry represent significant instances of the current and widespread interest in thinking processes.

This revival has occurred after a long period of disinterest among educators and psychologists in theories of general transfer. Thorndike's work on transfer at the turn of the century and his attack on faculty psychology and theories of mental discipline probably was the single most significant antecedent of this decline in interest. There followed a long period of educational research in which the major conclusion always seemed to be that transfer of thinking skills might occur but had to be taught for specifically. This view has prevailed until the recent interest in thinking processes which has been stimulated by the curricular innovations.

This project is in the spirit of the revival. It was stimulated originally by the observation that mere revision of content in science and mathematics courses did not seem to produce the massive change in thinking that some people seemed to expect. Even casual observation revealed that students did not intuit the logical structure of the new subjects, or even see the relation between concepts and principles learned in one topic to those learned in another. These observations are not offered as proof of the assertions made. They were the stimuli that prompted the ideas developed and tested in this project.

One aspect of these ideas is the general schemata for attacking any problem requiring analysis. This schemata might be called a "plan" for behaving in a problem situation. It summarizes the personal experience of one of the authors in research and invention and contains the principal features of several other summaries. It consists of two main parts: 1) The Familiarity-Hunch-Result search process employing Thinking Tools and 2) The Result expressed as "What is true, when it's true, and when it's not true." This material may be represented in a diagram as shown in Fig. 1.*

The process of Fig. 1 can be illustrated clearly as discussed in Sec. 2 with the aid of carefully selected games and mathematical problems with underlying principles closely related to laws of science.

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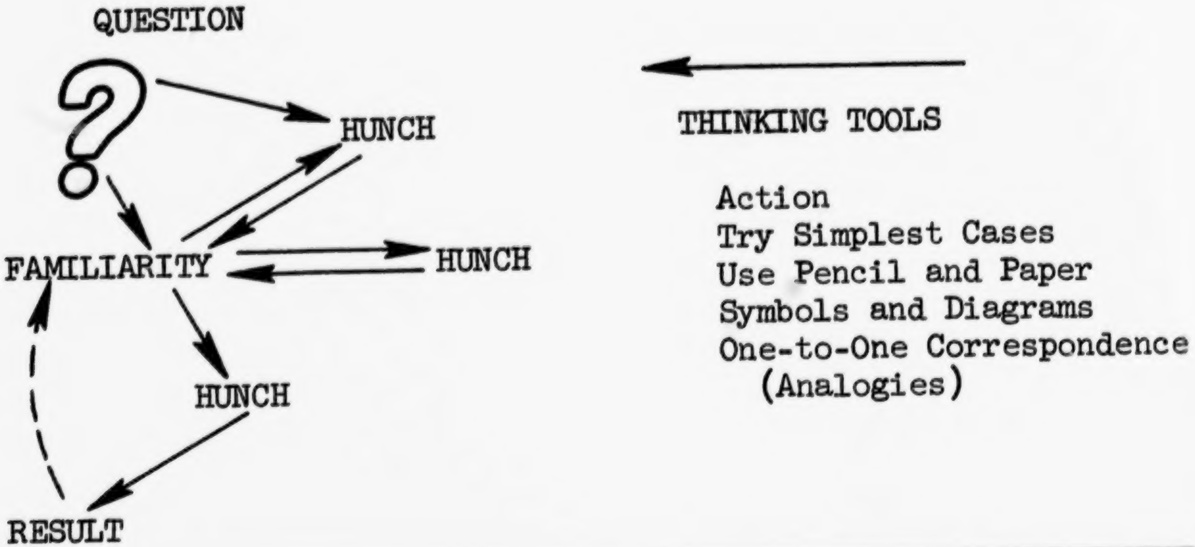
*This diagram presents essentially the same material as "Proposed important mental tools for scientific thinking at the high school level," W. Shockley, Science, 140, 1963, p. 384. See Section E and Chapters 2 and 3 for the current version of this diagram.


QUESTION
HUNCH
FAMILIARITY
HUNCH
HUNCH
RESULT
THINKING TOOLS
Action
Try Simplest Cases
Use Pencil and Paper
Symbols and Diagrams
One-to-One Correspondence
(Analogies)

WHAT IS TRUE ("Always true")
(A theorem, a principle or law, or an exact statement or equation)

WHEN IT IS TRUE ("no matter what")
(Range of application; examples)

WHEN NOT TRUE ("but not if")
(Area beyond range of application; examples)

Fig. 1. Shockley's representation of the thought process of developing a principle.

Figure 1 differs in an essential aspect from other outlines of the thinking process. To illustrate the relationships, three examples are quoted below:

> "Planning for Effective Science Teaching," T. G. Aylesworth, American Education Publications (1963):
>
> > "John Dewey outlined this (method of critical thinking) in a series of steps:
> >
> > (A1) Identify problem
> > (A2) Establish facts
> > (A3) Formulate hypothesis
> > (A4) Test hypotheses
> > (A5) Evaluate results."
>
> "How To Solve It," G. Polya, Doubleday Anchor Books (1957):
>
> > (P1) Understanding the problem.
> > What is the unknown? What are the data? What is the condition?

(P2) Devising a plan.
    Do you know a related problem? Look at the unknown! Here is a problem related to yours and solved before. Could you use it?
(P3) Carrying out the plan.
(P4) Looking back.
    Can you check the result? Examine the solution.

"A Technique for Producing Ideas," James Webb Young, Advertising Publications (1952):

(Y1) The gathering of raw materials--both the materials of your immediate problem and the materials which come from a constant enrichment of your store of general knowledge.
(Y2) The working over of these materials in your mind.
(Y3) The incubating stage, where you let something beside the conscious mind do the work of synthesis.
(Y4) The actual birth of the Idea--the "Eureka! I have it!" stage.
(Y5) The final shaping of the idea to practical usefulness.

A description closely resembling Young's outline is given in Hadamard, "Psychology of Invention in the Mathematical Field," Princeton University Press. In particular, Hadamard emphasizes the incubation stage (Y3) and its importance in many great discoveries. The close resemblance of the views coming from such different fields as mathematics and advertising (Young was founder in the Advertising Council, the creators of Smokey the Bear) suggests that certain features of the thought process of developing a new idea reflect characteristics of the mechanics of the functioning of the human brain and that this functioning or cognitive skill may be improved to a significant degree by teaching students the approaches based on the representation of Fig. 1.

The essential feature that Fig. 1 emphasizes in contrast to the other outlines is commonly acknowledged by most creative researchers: the process of developing a principle or bringing order out of chaos is not always orderly. The development seldom follows the logical (A1) to (A5) sequence of Dewey. Sometimes the problem cannot be identified clearly until the "Result" has nearly been obtained. In Fig. 1 the question mark labeled "Question" represents a wide range of possibilities including as one example a specific word problem in ninth grade algebra and as another vague feeling that somehow the low current-carrier densities in semiconductors can be controlled to make a useful electronic amplifier. In a case like the latter clearly identifying the problem was the main research objective that led to the transistor. In general, "question" is anything which provokes the brain into trying to establish some better order or understanding.

The most important thinking tool is "action." This helps to store in the active part of the brain the relevant materials among which new relationships may be discovered; the result of this storing is called "familiarity."* Intuitive appreciation of new relationships is called "Hunch." A wrong hunch may be valuable; it leads to more action and familiarity.

The "action," "familiarity," and "hunch" part of the representation corresponds to (Y1) (Y2) of Young, (P1) (P2) of Polya, and to some degree (A2) (A3). The final sequence from "hunch" to "result" (not actually as simple as shown; there may be more steps back to "familiarity") represents (A4) (A5), (P3) (P4) and (Y5).

The incubation or (Y3) aspect, which is vital in inventing such new concepts as the benzene ring, the junction transistor, and (it is conjectured) Smokey the Bear, is probably a necessity at the Ph.D. candidate level, whereas one can graduate from high school without learning it. It constitutes a somewhat higher state of sophistication than is represented in Fig. 1.

An example of a "result" used in the teaching experiment is a more exact statement of "What goes up must come down.":

> "It is always true that a solid object projected upwards on earth must return to the surface, no matter what it is made of, but not if it is accelerated to reach orbital or escape velocity."

If an appreciation of the disorderly aspect of discovery and of learning shown in Fig. 1 can be imparted, it may contribute to offsetting feelings of incompetence and distaste developed by students who are taught that the "only right way" is a logical sequence like (A1) to (A5). Such students may become "mathematics-haters." Some of these emotional aspects of the experiment are discussed more fully in Sec. 2.

To summarize the discussion above: One objective was to teach the process of search for an answer, and a second was to teach the logical structure of important principles.

The educational problem is to teach this set of concepts and their application in science. The research problem is to find ways of teaching these ideas that are effective.

Complex concepts of this kind are not easily taught. The temptation is simply to state them and to have students learn how to repeat them back in rote fashion. This instruction is obviously not likely to produce any depth of understanding or insight. In this project a set of simple, interesting games and problems was used as a way of helping students to grasp these concepts.

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*The large variations of scientific and inventive ability can probably be explained in terms of differences in capacity to store and compare ideas as well as in maturation. W. Shockley, "On the statistics of individual variations of productivity in research laboratories," Proc. Inst. Radio Eng., 45, 1963, p. 279.

All of these games were two or more person games, and generally resemble the board games with which most people are familiar. The first game used had the following characteristics: (1) a general principle could be formulated which predicted who would win the game; (2) the assessment of who would win was not immediately obvious, nor was it apparent either that the winner had invariant characteristics. In these regards the principle of the game resembled a law of nature. Typically a game began with no awareness of who was going to win, proceeded to a phase in which a description of some kind could be given of the winner, and from there gradually to a formulation of the principle that explained who would win.

The first game taught required data-gathering, making hypotheses, testing them, and eventually formulating a principle. The principle or "law" of the game could be stated as something that was invariantly true given a set of conditions. In these ways identifying the logical structure of the game resembled establishing a scientific principle in keeping with Fig. 1.

The game discussed and other games in which the outcome depended on understanding and applying a principle were introduced to students as something interesting that they might like to learn and to play competitively with each other. Usually, the games were preceded by a brief description of the model of thinking explained above, and the games were described as requiring the kind of thinking one goes through in establishing scientific facts. The purpose of the games is to serve as device for illustrating the processes required in scientific thinking, the difficulties involved, and the logical structure of laws and principles under circumstances in which the student becomes actively involved.

The second problem is to apply this way of thinking to scientific problems. A series of experiments were devised to teach the concept of potential energy as an explanatory concept that underlies such principles as those of levers. The strategy in these experiments resembled that in the games. The student was presented with some data gathering to do, such as finding the center of gravity of an irregular object. The object was moved through several positions; in each case the student is asked to predict how the object will hang from a support--like predicting who will win the games. Then a principle is called for, to organize and express the invariance in the observed phenomena. Similar experiments are repeated in which the strategy is carried out, and which extend the student's understanding of the scientific principle or concept he has learned.

The games serve the purpose of introducing the concepts and the strategies in an interesting way. The experiments extend and apply the ideas. The hoped-for attainment is the acquisition of a way of thinking about problems, and an insight into the invariant character of scientific laws and the thinking processes involved in their development.

Methodology

The work described in this study was conducted in two parts. A 15 week teaching session was held with 150 ninth grade students at Wilbur Junior High School in Palo Alto. These classes were taught by three teachers in a team teaching arrangement. The classes were selected because they represented a spread of ability and because the teachers were interested in the study and willing to cooperate in its execution.

These teaching sessions had two major parts: (1) in the first the students were taught the logical games referred to above; (2) in the second, they conducted a number of experiments to derive a scientific principle.

This sequence of events was repeated in a teaching session during the following summer. The purpose of this second trial was to test the ideas of the study under more favorable conditions. A smaller class, 30 in number, and only one teacher was used. An innovation in the method was also tried at this time. Half of the group was originally taught by the teacher, and then this group was used to do some of the teaching to the same half.

Treatments. In both of these studies* the set of games was used to teach the steps in thinking through to a problem solution, and the way in which to formulate a general principle or law. The set of experiments required similar thinking processes. The students gathered data which led to the derivation of a general principle.

The following is a description of one of the games used for teaching purposes, the "Take One to Five, Last Match Wins" game. This is a two-man competitive game. The object of the game is to be the player who takes the last match (matches, paper clips, or similar objects are used as counters in the game; marks on a blackboard can be used equally well in a classroom demonstration). The players sit with a pile of matches of some arbitrarily chosen number, such as 25, between them. Chance determines the first play. Each player in turn takes matches from the pile. He may take as few as one or as many as five, or any number in between, at each play. The player who removes the last match, leaving none for his opponent, wins.

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*Reports by teachers of both experiments are given in the appendixes to the cited 1964 report.

Students playing this game discover quickly that six is a winning number. If six matches are left, obviously the player who left them will win, no matter how many matches his opponent takes. His opponent can take no more than five, thus leaving one or more up to five which the winner can take. The next step for the student is to discover that leaving his opponent a group of 12 matches also guarantees winning, because after the next two plays it can be reduced to a group of six.

These experiences lead the student to the "hunch" that leaving groups which are multiples of six will insure a win if he plays properly. This hunch can be tested in repeated plays and verified. At this point the student has grasped the basic principle of the game at one level of understanding. Then the student is taught to state the principle in a form described in Fig. 1, a form requiring him to state "what is true," "when it is true," and "when it is not true":

> "It is always true that the player who leaves a group of six or some multiple of six matches will win; no matter what plays his opponent makes; but not if he makes an error on a subsequent play."

At this simple level the student has grasped and stated a basic relationship describing the game. However, a much deeper understanding of the principle underlying the game may be achieved. At this point the student is urged to state the principle in terms of the fundamental mathematical relations implicit in it. This more abstract and more general statement is as follows: "It is always true that a player can match his opponent's play so that the sum of their plays is six, no matter what play his opponent makes, but not if there are less than six matches when his opponent plays." In this form, the principle can be applied to a highly similar game, but one in which the player forced to take the last match loses. The student learns in this way the utility of general principles.

One of the advantages of using these games is that their subject matter is simple. Attention can be focused on the logical structure of the problem, which is sufficiently difficult, without having to acquire many new concepts and facts. Also students can be taken quickly with the games through the steps in scientific investigation using a minimum of laboratory equipment.

Another characteristic of these games is that success in them depends on understanding. If a student grasps a principle, he not only knows the conditions under which he will win, but he also understands when he will lose and why. Obviously, in some of the games even Einstein could not win under certain conditions. The student learns the relation between the cognitive and emotional aspects of problem solving.

They may also learn that in competitive situations understanding, thinking, reasoning gives them an advantage, and confidence that they will not always be "outsmarted." These competitive games are "real-life" situations--the opponents are really playing against each other to win, and winning brings recognition and satisfaction. The experience of thinking through a problem in a real-life situation like these may help the students learn that mathematical, logical, and scientific thinking may be used effectively in coping with life problems. A hoped-for consequence would be that this learning would stimulate greater interest in the value of mathematics and science as ways of solving problems.

In summary, the games are designed to teach what is required intellectually and emotionally, to solve a problem that involves using new logical structure. They are designed to demonstrate the general validity and utility of this kind of thinking.

These experiences with games are meant to introduce the student to a general way of thinking which he can apply in science. The question is, then, how is a bridge made between the games and the scientific experiments?

The result of each game-playing experience is the formulation of a general principle. This principle is a statement of invariance under a set of conditions. The students are being taught to look for such invariances, because they are the devices for explaining, predicting, and describing what has been observed. The experiments to be described below are the means for gathering data which will lead to the discovery of a scientific principle, an invariance, that will explain these observations.

The first experiment was called, "Experiment on Hanging a Rigid Body."

* * *

Since this experiment, and other aspects of the 1964 report are covered in subsequent sections, we omit their repetition here.

D. The Proposal for This Contract

The proposal for the present contract (OE 6-10-026) was based on the findings and insights gained from the Wilbur experiment described above. The proposed objectives and procedures, as quoted below, have been met except for the student-teacher-student procedure which was abandoned because of difficulties of its administration.

Objectives

The primary objective is to develop for the ninth grade an experimental teaching procedure and related evaluative instruments to measure the effectiveness of teaching directed towards an understanding of and appreciation for the concepts of energy and the law of conservation of energy. Several additional objectives constitute significant steps along the route to the primary objectives. The experimental teaching procedure is planned to impart an appreciation of the invariant and useful character of conservation laws by utilizing simplified examples in the form of selected games and puzzles having logical structures similar to the laws of nature, especially to the conservation laws. Thus additional objectives are to develop teaching materials to encourage the transfer of learning from competitive game situations to an understanding of several scientific principles and to develop measuring instruments to evaluate the effectiveness of this procedure. The developments undertaken should lead to improvements in experimental and tentative teaching methods and devices which could develop into a unit of instruction on energy suitable for incorporation in ninth grade science in any high school. A more effective use of energy concepts is vitally needed in subsequent high school science courses, especially eleventh grade chemistry since it often precedes the study of physics.

Procedures

The experimental field test of this material will be carried out chiefly in the junior high schools of the Palo Alto Unified School District. The limited scope of the material planned for the energy unit makes possible repeating it successively several times during the school year. The starting material will use apparatus and text material already used experimentally in early 1964. Two ninth grade teachers will be employed to conduct the teaching, so that approximately six classes (corresponding altogether to about 150 students) will be taught during each session of presentation of the material. Additional teachers or graduate students will assist in preparing text material and revising it during the successive teaching cycles. The effect of active participation in the learning process will be enhanced in two ways: by using competitive games and by using the quicker student learners to teach the slower learners. The latter purpose requires an experimental facility comprising approximately 10 three-student cubicles (with extra space for teacher observation and participation). Specially relevant eighth and ninth grade mathematical material will be taught or reviewed. Tests to evaluate comprehension and retention of the material will be developed and used in the ninth grade, and also in a follow-up program in later grades.

Description of Activity

Activities under this program will be focused on teaching both insight into the logical structure of natural laws of science and understanding of the processes which lead to the discovery of laws. The procedure is based on preliminary research findings that the desired insight and understanding can be hastened by a transfer of learning from other logically related material. The particular material consists of selected games and puzzles having logical structure similar to important quantitative scientific laws.

Emphasis will be placed on the concept of conservation or invariance in science, with particular applications to conservation of potential energy in levers, pulleys, and hydrostatics (Pascal's law and Archimedes' principle). A set of evaluative instruments will be developed to appraise the success of the basic approach and of the teaching methods and materials. An important aspect will be a follow-up in a subsequent school year to measure retention of the material taught and its effect on performance in related subjects.

* * *

An illustrative problem which has been used successfully in the teaching is the "tennis tournament" problem. [This example is fully described in Section E.]

* * *

The principle for the tennis tournament problem is the important result or product of the research process. To proceed from the hunch to a real understanding of the principle and then to the efficient stating of the principle is not at all easy; it requires perseverance and ingenuity. Learning this fact from the firsthand experience with games and puzzles can increase the students' respect for the neatly stated laws of science.

Related Literature

The need for energy concepts to be developed prior to the eleventh grade in high school is clearly brought out by the subject matter of the material produced by the Chemical Education Material Study ("CHEM Study") prepared under a grant from the National Science Foundation, with a text entitled *Chemistry: an Experimental Science*, published by Freeman and Co., San Francisco. This text makes extensive use of the energy concept, especially in regard to the relationship of thermal energy, activation energy, and reaction rates. Energy also appears in the form of electrical energy in electrical cells and electrostatic potentials. A foundation for these energy concepts is developed in a brief way in this course but does not properly constitute its subject matter. At present no prior course lays the foundation.

Also, in modern physics courses such as the Physical Science Study Committee material (also developed under a grant from the National Science Foundation), it is assumed that concepts of levers and potential energy will have been developed at an earlier grade.

The methods of attack in this program are in many regards similar to those discussed in the well-known book by George Polya entitled How To Solve It (Doubleday and Co., New York, 1957). Compared to Polya's approach, emphasis in this proposed program is on a more restricted range of logical content, with special emphasis on general principles which are similar to the conservation laws and principles of invariance in natural science.

Related psychological literature relevant to the ideas behind the proposed project may be found in:

H. G. Birch, "The Role of Motivational Factors in Insightful Problem-Solving," Journal of Comparative Psychology 38, 295-317 (1945).

K. Duncker, "On Problem-Solving," Psychological Monographs 58, 5, 1945 (Whole No. 270).

B. Ghiselin, ed., The Creative Process (University of California Press, Berkeley, 1952).

Mary Henle, "Some Effects of Motivational Processes on Cognition," Psychological Review 62, 423-432 (1955).

Mary Henle, "On the Relationship between Logic and Thinking," Psychological Review 69, 336-378 (1962).

H. Poincare, Science and Method (Dover Publications, New York, 1952).

A. Newell, J. C. Shaw, and H. A. Simon, "The Processes of Creative Thinking," in Contemporary Approaches to Creative Thinking, H. E. Gruber et al., eds. (Atherton Press, New York, 1963).

M. Wertheimer, Productive Thinking (Harper, New York, 1959).

Support for the puzzle and game approach as a sound teaching technique is found in serious science texts. For example, "CHEM Study" uses a number of such devices, in particular the "garbage collector" analogy to describe the research approach and the "black box" puzzle to indicate how data can be collected and hypotheses formed. An excellent example of a similar viewpoint is found in Feynman's Lectures on Physics (Addison-Wesley, 1964), a product of the physics courses for students at the California Institute of Technology. Feynman illustrates the energy concept, the conservation laws and their logical relationships in terms of the conservation of toy blocks in a playroom.

A systematic collection of puzzles and games to bring out the relevant logical features does not appear in any published form. The set of examples collected and invented by the senior investigator thus appears to constitute a new teaching tool. Dr. Shockley presented the basic outline of this idea at the April 1963 meeting of the National Academy of Sciences (see Abstract in Science 140, p. 384, April, 1963). [See also Section B of this chapter, p. 6.]

Specific Objectives in More Detail

There are a number of interrelated objectives for this program. The six most significant objectives are underlined.

(a) Experimental Subject Matter

The first major objective is to teach the concept of conservation or invariance in science, with emphasis on conservation of energy. Conservation of potential energy applied to levers, pulley and gear systems, and hydrostatics (Pascal's law for pressure and Archimedes' principle for buoyancy) constitute specific examples to be taught.

An additional objective is the understanding of the general format or principal logical features of a quantitative law of science.

* * *

The second major objective is to teach a thinking process of discovering or learning a new law or new principle.

* * *

A further objective is to develop teaching and evaluative tools for teaching the methods of discovering logical processes and formulating principles by means of games and puzzles.

Also planned is the development of teaching methods to relate laws of levers, pulleys, and hydrodynamics to conservation of energy, in particular potential energy for frictionless systems. (There is no known ninth or tenth grade physical science material at the present time which deals with this subject matter in a form consistent with the logical emphasis now given in mathematics at the same grade levels.)

(b) Experimental Teaching Methods

A number of novel teaching methods will be emphasized in the program. Several important objectives are related to improving these methods and developing instruments to evaluate their effectiveness. (Procedures for meeting these objectives are described particularly in Sections 5(c) and 5(d) of the proposal.)

The third major objective has the dual purpose of developing teaching procedures involving competitive games and puzzles to stimulate interest in the logical structures that constitute the subject matter of this proposal and of developing related evaluative instruments.

The fourth major objective will be to develop and to appraise the learning and teaching processes that utilize quicker learners to help teach slower learners in a formalized, controlled environment. [It was not possible to carry out this procedure because of administrative difficulties within the schools.]

Another objective will be to evaluate the relative merits of different sequences of using puzzles and games in respect to science, so as to find out what is the optimum mixture and sequence to achieve the most effective educational results.

(c) Research Instruments

The fifth major objective is to develop evaluative instruments which will appraise changing ability to learn logical structures, to formulate laws, and to apply laws. (Some examples of experimental instruments and results are discussed in Section 10 of this proposal.)

It is planned to use these evaluative instruments in appraising the different teaching procedures that will be carried out and to follow up the degree to which the material is retained over a longer period and applied to relevant subsequent technical courses.

(d) Representative Teaching Experiment

It is planned to hold a summer institute to teach ninth grade general science teachers and eighth and ninth grade mathematics teachers. This should meet the sixth major objective of ascertaining the nature of the problems associated with introducing the energy unit into a school system.

E. The Steinmetz Lecture and the General Philosophy of the Project

The general philosophy and some of the principal investigator's personal experience relevant to this project were presented as the 37th Memorial Steinmetz Lecture. This was subsequently reprinted in the IEEE SPECTRUM. This article is inserted in its entirety so as to show the relationship of this approach to engineering education, as well as to describe aspects of the teaching philosophy valid at any level.

The article encompasses pages 21 through 30 of this report, but the pages are not so numbered in order to avoid confusion with the reprint page numbers.

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Articulated science teaching and balanced emphasis

The experiences that stay in our memory are those that are dramatic, or are exaggerated, or are unusual in some other way. Teaching experiments have shown that this principle can provide us with a useful scientific thinking tool

William Shockley *Stanford University and Bell Telephone Laboratories, Inc.*

The set of scientific thinking tools described is based on dramatized, exaggerated patterns of logical structures. What these patterns have in common is an overall invariance relationship that makes something true even though the details may differ in different situations—and a knowledge of that relationship leads to simple solutions of apparently complex problems. Articulated science teaching is defined as a method of getting the invariance concept across to the student by using selected puzzles and games as exercises in logical thinking. The end result should be to improve rational reasoning ability both in science and in everyday life.

Prologue

"One objectionable feature of the instruction of most colleges is the step by step method. One subject is taken up, by application of sufficient time and energy pushed through, and then after passing an examination dropped to take up another subject. It is true that by steady application to one subject a great deal can be learned and splendid results derived in the examination papers, but all that is learned in this manner is just as rapidly forgotten. To understand a matter thoroughly, so as really to have a lasting benefit from it, and not merely make a good showing in examination papers, requires several years' familiarity. *Therefore, any subject that is not kept up during the whole college course might iust as well be dropped altogether and the time spent therein saved*. . ."

"What then, should an ideal electrical engineering course contain?

"Of mathematics, plane and some solid geometry, arithmetic, and a good knowledge of algebra. Plane trigonometry—no spherical trigonometry required—and a thorough understanding of analytical geometry and of calculus, but no memorizing of integral formulas, etc.; they can always be looked up in a book when needed.

"A thorough knowledge of general physics, *especially of the law of conservation of energy*, which I am sorry to say is not yet an integral part of our thinking, and of chemistry, especially theoretical chemistry and the chemical laboratory, in the latter freely using tables, etc.

"The electrical laboratory work should be taken up right at the beginning. Even before taking up the theory of apparatus, the theoretical investigation of alternating currents, self-induction, transformers, etc., the student should have met these phenomena and handled the apparatus in the laboratory. Only after seeing the effects of self-induction, for instance, on the alternating current circuit in the laboratory, will the theory of self-induction, have any meaning or *make an impression on the student*. What the student has seen practically in the laboratory he will then take up in the theoretical course, and understand it; he will learn to calculate and control, and afterwards, going back once more to the laboratory, to apply it. It is here that the average college graduate is inferior to the practical man, and in spite of his handicap regarding theoretical knowledge, the latter frequently pushes ahead of the college graduate because of his superior understanding of the phenomena, based *on his familiarity with them*. . ."

Charles Proteus Steinmetz expressed the views quoted above (except for the emphasis added by the present author) in his 1902 presidential address to the AIEE. The reader will find much in common between Steinmetz' views, especially the emphasized phrases, and the article that follows. Any common conclusions are quite independent; this article was completed before the writer had read the Steinmetz address.

Principles of invariance

Around 1925 I had one of my earliest and most memorable experiences with the power of scientific thinking tools. I was marked wrong on a physics problem that I thought I had solved correctly. The problem consisted of calculating the propelling force required to keep a rowboat in motion. This force was produced by a man pulling with a 25-pound force on each oar handle. The distance from oar handle to oarlock was 2 feet and that from oarlock to blade was 5 feet.

The correct way to do the problem, my teacher insisted, is as shown in Fig. 1. First, regard the oar blade as a fulcrum. The lever arm for the man's 25-pound pull is then 7 feet. Next, calculate the force F_o exerted on the oar by the oarlock; the law of levers gives $25 \times 7 = F_o \times 5$ so that $F_o = 35$. This would give 70 pounds pushing the boat forward, but the man pushes back on his seat with 50 pounds. Therefore, the net force on the boat is $70 - 50 = 20$ pounds.

I calculated F_B, the push of the water on the oar blade, using the oarlock as fulcrum: $25 \times 2 = F_B \times 5$, so that $F_B = 10$. However, the push on the blades is the force pushing the boat-oars-man system forward. This force is thus 20 pounds—the same answer.

This solution was not acceptable to the teacher; it did not actually calculate forces on the boat. We argued. I tried to bring in an outside authority, a university professor whom I knew, but he was a professor of education and did not wish to become involved. I remained convinced that my method was sounder and simpler than the teacher's.

This is but one of a number of similar examples I remember from high school. They all had a common feature—some overall principle permitted an answer to be reached that was *always true no matter* what the details.

One of the best known of these problems was that involving the bee and the motorcyclists: two motorcyclists start from a common point and proceed at 30 mi/h in opposite directions on a circular racetrack. Simultaneously, a bee starts from the same point and flies at 60 mi/h in precalculated straight-line chords (not pursuit curves), intercepting the cyclists alternately until it is crushed between their noses when they meet. The circular racetrack is approximately 10 miles in diameter and the circumference is exactly 30 miles. What is the total length of the bee's path? That is, what is the sum of all the straight-line chords? (You may, of course, consider the idealized limiting case of point travelers and infinite accelerations.) As I recall the situation, I solved this problem on my own, thereby impressing the college student who had posed it to me. This was a dramatic experience. He was a big man in my eyes, farther along in college than I was in high school. I was impressed with my own accomplishment.

A similar problem that I was given at about the same time involved a string around the earth's equator. Suppose this string makes a snug fit. Cut it and add 3 feet, then form it into a new perfect circle at a height h above the ground. Can you insert a pencil under it? I began by converting 8000 miles to feet, multiplying by 2π, then adding 3 feet, and before I finished (I probably bogged down) someone told me how to use the algebra I knew.

The rowboat, the motorcyclists and the bee, and the string around the equator are what I now call dramatized, exaggerated patterns of logical structures. What do they have in common? In each case, there is an overall invariance relationship that makes something always true, no matter what the details may be. These invariance relationships become more apparent when they are expressed in parallel forms as follows:

In the rowboat situation, it is *always true* that action (the back push of the boat system exerted on the water by the oar blade) equals reaction (the forward push of the water on the boat system) *no matter* what internal forces exist between man and seat, man and oar handles, oars and oarlocks, etc. (*but not if* turbulent drag is included as part of the force on the boat; this obviously was not intended in the problem).

In the racetrack problem, for every unit of distance traveled by a motorcyclist, the bee travels two units. This invariance relationship shows that it is *always true* that the bee flies 30 miles while each cyclist does 15 miles *no matter* whether the bee flies chords, pursuit curves, or hexagons in the middle of the racetrack, *but not if* the bee's time does not match that of the cyclists or if the acceleration of the bee must be included.

The parallel sets of emphasized phrases exhibit the structure of the qualified law form discussed more fully later in this article. They emphasize that having a principle well under control means knowing not only *what* relationships it asserts, but also *when* it does apply in terms of specific examples and, furthermore, *when not*, again in terms of specific examples.

For the string around the earth, the key relationship is "circumference equals 2π times radius." Consequently, it is *always true* that each 2π feet of increased circumference gives 1 foot of height *no matter* how big a circle we choose, *but not if* our precision of discussion should include curved space effects due to the earth's gravitational field.

The invariance principles in these examples lead to simple solutions of apparently complex problems. The power of conservation laws and invariance principles to dispose of details and go directly to the answer has always seemed to me to be among the more appealing esthetic aspects of theoretical sciences. Can this combination of elegance and utility be taught? Can these methods be made more useful to science and engineering students? Can a sympathetic appreciation of them be imparted to nonscience majors?

Transfer and the articulated science approach

About seven years ago I tried to help a science student who was studying PSSC physics. The problem in question involved index of refraction. I shall give the discussion in brief; understanding the details is not essential to following my general line of thought. In trying to impart understanding, I pointed out that since $n_1 \sin \theta_1 = n_2 \sin \theta_2$, the quantity $n \sin \theta$ is conserved as a light ray crosses a plane of discontinuity of refractive index n at angle θ away from perpendicular incidence on the plane. The same will be true for a set of parallel plane slabs. Hence a light ray entering from air into a stack of parallel slabs will emerge at the far side into air on a path parallel to its entrance because $n \sin \theta$ is the same for incident and emergent rays, and so is n. Therefore, so is θ, and equal θ's mean parallel rays.

In summing up our original extended discussion I said, "It is like a conservation-of-energy principle." This went over like a lead balloon.

Articulated science teaching, as defined in the remainder of this section, is my attack on getting the invariance or conservation law concept across.

Articulated science has a logical parallel to a device in electrical engineering. This device, named the *dissected amplifier* by Mason and the writer,[1] shows that negative resistance plus nonreciprocal circuit elements can be combined to construct amplifiers. The dissected amplifier is composed of two spatially separated parts: ac power generation and one-wayness. In the amplifier these parts are articulated in combinations that have, for example, the four-terminal characteristics of an ideal pentode.

Somewhat similarly, articulated science teaching dis-

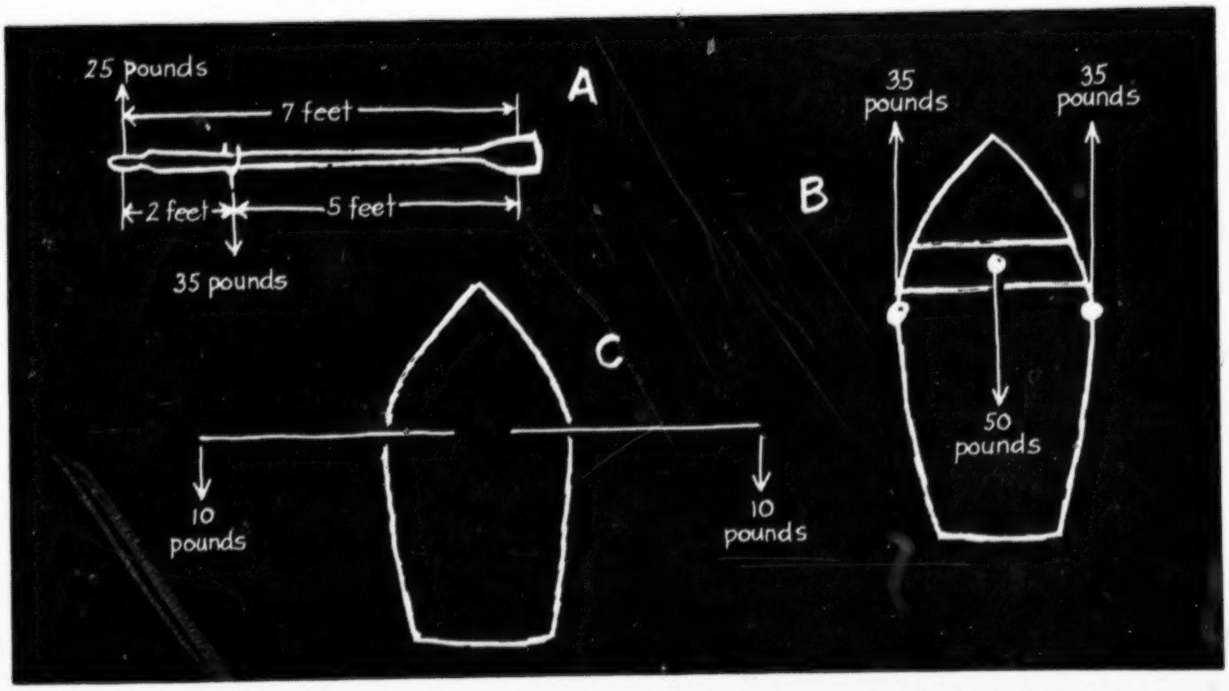

Fig. 1. The rowboat problem. A—Moments on oar with blade as fulcrum. B—Net forces on boat. C—Forces of oar blades on water.

sects the pedagogical problem into several smaller steps. Logical structures are introduced that have conservation principles.[2] These deal with very simple subject matter, such as counting piles of matches or paper clips. Then concepts of quantitative attributes of nature are developed, such as weight, length, or moment. The student can transfer the concepts of invariance from the subject matter of games and puzzles to the scientific subject matter. The recognition of a significant quantitative attribute such as a moment becomes more immediately meaningful; thus the logical structure concepts are articulated with the concepts of quantitative physical attributes of nature. An additional aim is to provide an experience of active participation in developing scientific concepts. The new teaching approach uses the tried-and-true technique of dividing and conquering. Articulated science teaching dissects the pedagogical problem into two smaller parts.

Provoking and observing a transfer of the concept of conservation in games and puzzles to the concept of conservation of energy gave me one of my most exciting teaching experiences. In the summer of 1963 I had taken four or five volunteer eleventh grade students through the logical structures of three or four selected games and puzzles. These (one of which I shall describe more fully presently) were the tennis tournament problem, the *n*-acquaintance problem, and the checkerboard problem. After searching out and stating in qualified law form the principles of these problems, I had led the students to establish experimentally the law of levers.

With these experiences as a basis, I then posed some hypothetical problems in which a set of weights was to be rearranged on a set of shelves. The conceptual operations to be done on paper were restricted to those that could be performed using balanced levers. In other words, some weights were lifted at the expense of equal losses of potential energy of other weights. I chose the first three problems so that there was no change in total potential energy. The students soon worked out solutions. Then I gave them an impossible problem in which the potential energy increased significantly.

These students had had little, if any, previous experience with quantitative energy concepts. Potential energy had not been mentioned in my class.

After five or ten minutes the conversation went like this:

Kathy: "I don't think it can be done."
Teacher: "Why?"
Kathy: "It doesn't add up."
Teacher: "What doesn't add up?"
Kathy: "I think the weights that go down times the distance they go down must equal the weights that go up times the distance they go up."

Another student, who had not concluded anything about the problem so far, observed: "Those are foot pounds. That is a form of energy."

My conviction is that Kathy had realized that this problem had the feature, "You can't do it, no matter what." This she recognized from the game experiences as a clue that a conservation law was involved. The games had been deliberately selected so as to exhibit conservation laws. They had the "you can't ever, no matter what" feature common to efforts to make perpetual motion machines, or to produce gold by alchemy, or to beat a gain–bandwidth product. Kathy sensed this situation and found the relevant invariant attribute, namely, sum of weight times height, or at least the significance of its changes. By carrying the concept of conservation from the games to potential energy, Kathy made my teaching experiment a success. Later I learned that this process is called *transfer* in educational psychology.

My teaching experiments have been directed toward imparting dramatized, exaggerated patterns of logical structures for transfer in scientific thinking. How can this be done? Why this emphasis on exaggeration and dramatization?

People remember things that are dramatized, exaggerated, or grotesque, or are striking or unusual in some

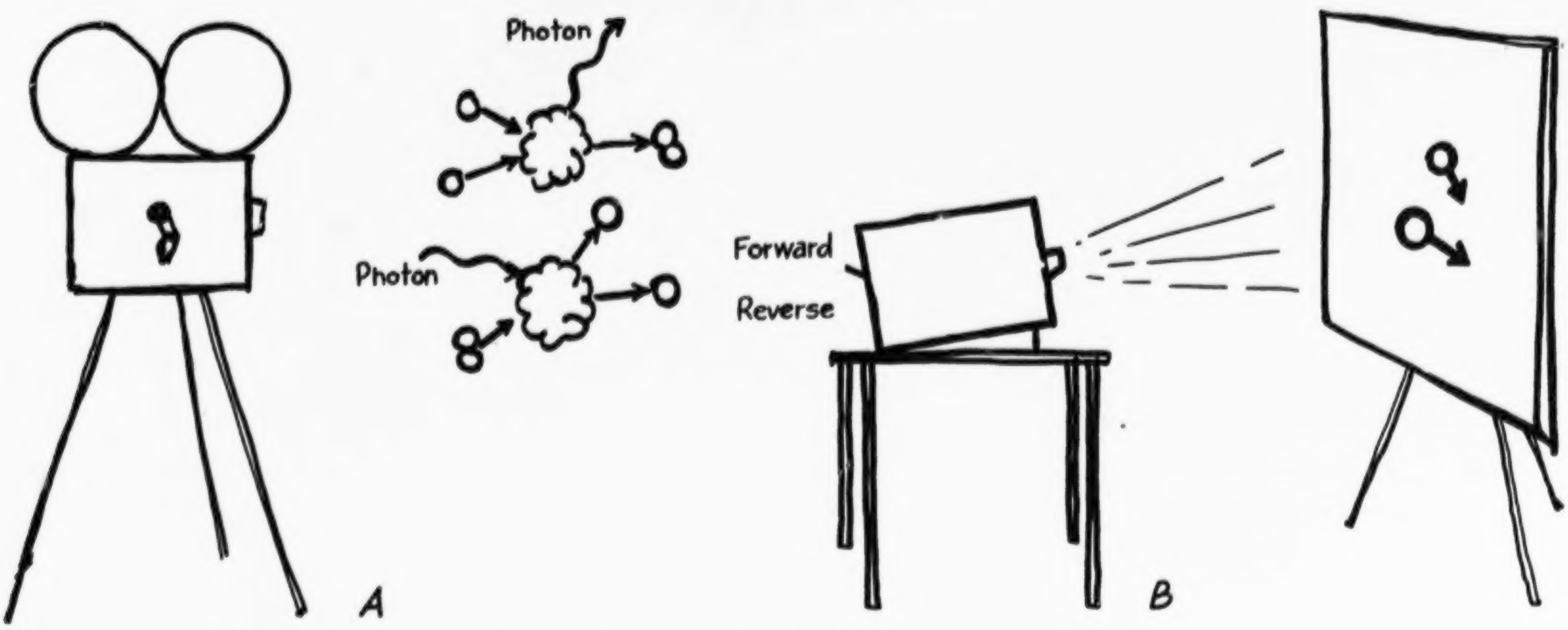

Fig. 2. The principle of detailed balance. A—The dramatized, exaggerated, and even grotesque idea that a movie can be taken of atomic processes, including the flight of photons. B—A similar idea that the movie can be projected and you can't tell by looking at it whether it is being run forward or backward.

other way. This fact is exploited in the techniques of memory stunts.

My favorite example of a dramatized, exaggerated pattern involves the principle of detailed balance. This has been one of my most useful scientific thinking tools. As I remember hearing it in a statistical mechanics course from my M.I.T. thesis professor, J. C. Slater, the basic idea is this: When a system has come to thermal equilibrium, it is going nowhere. Past and future are alike to it. On the average, for every time two atoms collide to form a molecule, a molecule will split into two atoms. Forward and reverse reactions balance in detail.

Suppose, as shown in Fig. 2, you could take a movie of this process (a grotesque, exaggerated idea indeed). If you projected this movie, you would not be able to tell whether it was running forward or backward. This invariance to reversal leads at once to equations that often are new, useful, and publishable results. Einstein's stimulated emission coefficients[3] and the Nyquist[4] derivation of Johnson noise are classic examples.

The reader prepared for more technical details may be interested in the following applications to the Shockley–Read recombination theory[5] in semiconductors: Suppose empty traps in a semiconductor capture electrons at a rate $nc_n n_t f_p$ (where n = electrons/cm^3, c_n = capture constant cm^3/s for empty trap, n_t = traps/cm^3, f_p = fraction of traps empty). Suppose also that the rate of emission of electrons out of traps is $e_n n_t f$(e_n = emission constant for full trap, $f = 1 - f_p$ = fraction of traps occupied by electrons). Then detailed balance says if in one second in one cm^3 you observe $nc_n n_t f_p$ electron captures, you must also observe exactly the same number of emissions. Why? Because if you run the movie backward, capture looks like emission and emission like capture. If the rates aren't equal, then you can tell the difference between forward and reverse movies, and according to detailed balance you can't be at equilibrium. Hence you can conclude that

$$nc_n f = e_n(1 - f)$$

This is actually one way of deriving the Fermi–Dirac distribution, as may be seen by first solving for f:

$$f = \frac{1}{1 + (nc_n/e_n)}$$

Next, show that this is the Fermi–Dirac factor by noting that for nondegenerate electrons $n = N_c \exp{(F - E_c)}/kT$, where N_c is conduction band density, F is the Fermi level, E_c is conduction band edge, and kT is thermal energy. Then f is seen to be correctly the Fermi–Dirac distribution function. This is a simple example of the power of the detailed balance principle. My own work has used detailed balance numerous times.[6,7]

Three scientific thinking tools

Examples of logical patterns that have been tried in a ninth grade articulated science teaching experiment[8] are contained in two "take-away" games that resemble the famous "take-away" game of Nim. These games are played with one or more piles of objects such as paper clips or matches.

"Two pile" is played with two piles of matches with, say, ten matches in each pile to start. (This comes out even with a 20-match book of paper matches.) Two people play. For his play, a player may remove one match from either pile, or one from both; in other words, he has three possible plays. If there is only one pile left, he must take one from that pile. The winner is the one who takes the last match, leaving his opponent with no possible play.

"One to five" is played with one pile of, say, 20 to start. On his play, a player must take at least one match, and may take two, three, four, or five. Again, the winner is the one who takes the last match, leaving none for his opponent. (Alternate variations of both games make the loser the person who is forced to take the last match.)

Each game has its own principle, and knowledge of that principle enables one to win unless his opponent also knows it or happens to be lucky. The games are taught to dramatize the power of mastering a logical principle. Half a class learns one game, and half the class the other game. Students then pair off and play the two games alternately.

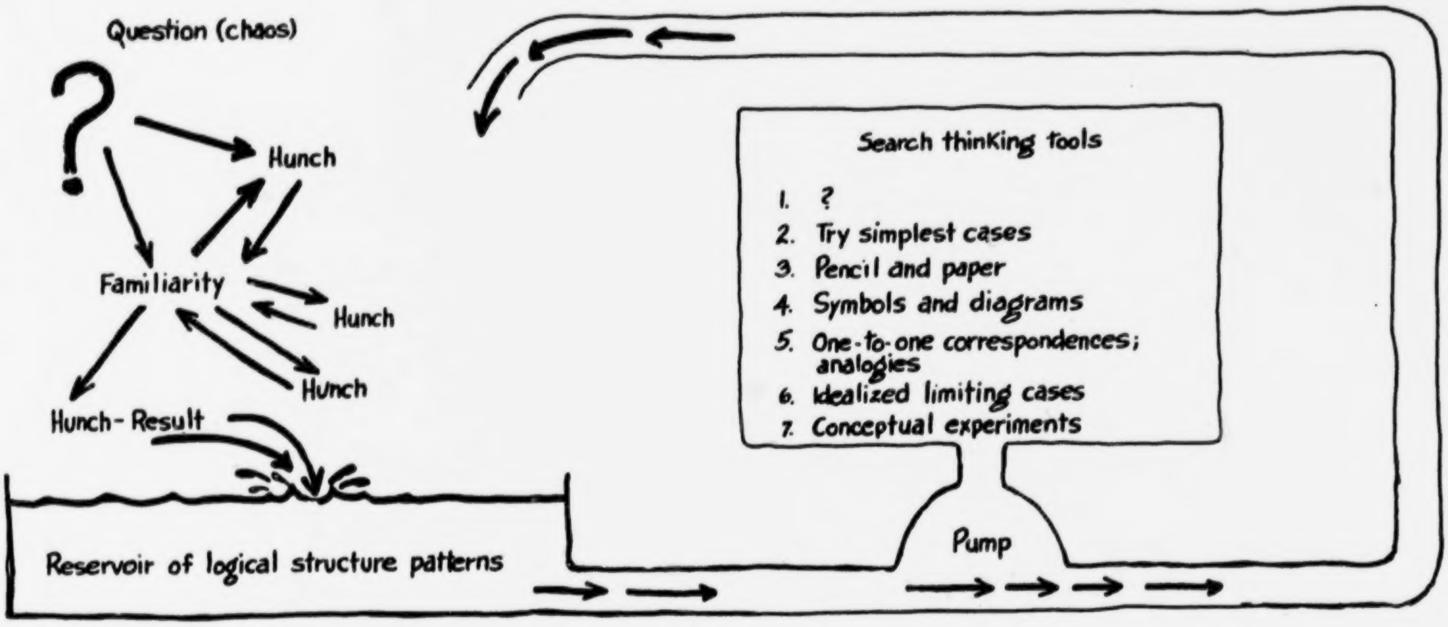

Fig. 3. The creative search pattern and seven search thinking tools.

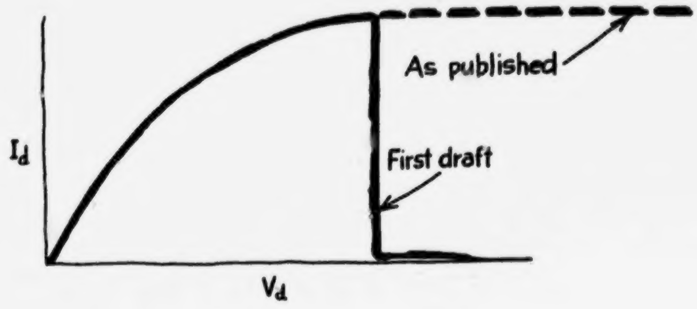

Fig. 4. A bum hunch about pinch-off in the field-effect transistor.

These games can be used as dramatized, exaggerated examples of three important scientific thinking tools: (1) CSP—the creative search pattern (including the "search thinking tools"); (2) ACOR—(key *a*ttribute)-(*co*mparison operation)-(result, an orderly *r*elationship pattern), of which postulate-proof-theorem is an example; and (3) QLF—the qualified law form for a result.

The creative search pattern[2,8] of Fig. 3 has a family relationship to similar forms in various writings on the creative process. To a greater degree than any others I know, it portrays the disorderly, frustrating aspect so often present in creative work. I can illustrate the role of the hunch of Fig. 3 by telling some stories on myself.

When I first worked out the gradual approximation for the field-effect transistor, I had a wrong but very useful hunch about pinch-off. (Pinch-off is now, I think, perfectly clear and obvious in the literature.[9,10]) My hunch led to the first plot of drain current I_d vs. drain voltage V_d, as shown in Fig. 4. I thought this characteristic would make a wonderful switch, and I circulated a draft memorandum in which I explained how it worked and prophesied its utility.

The more I thought about my idea, and became familiar with pinch-off concepts, the more unreasonable it seemed. Then the key attribute of saturation current became obvious; the influence of gate and drain voltage effects was compared by mathematical operations involving exponential attenuation of drain voltage effects. This was the needed ACOR pattern. I rewrote the memorandum and published it.[9]

The whole creative search process ends with a result. In this case the orderly functional relationship between drain current and drain and gate voltages constituted the now-classic analysis of the field-effect transistor. The CSP history involved alternating between hunches and familiarity for about six years. The hunch that a field-effect transistor really might be worth analyzing followed, as I recall, the stimulus of advancing semiconductor technology. The published output was a significant new ACOR pattern.

When I heard a few years ago that a copy of my "bum-hunch" draft memorandum still existed, I was distressed. But now I use its existence as a teaching tool. After I have told the story to a graduate seminar, I can refer to it to give perspective to comparable blind spots in the thinking of my students. I can say, "That reminds me of my first field-effect transistor manuscript." Most students can then be objective and carry out some valuable and constructive analysis of their own thought processes.

The story also illustrates another of my precepts for doing research: Don't expect to avoid mistakes; acquire familiarity and get better hunches by taking action and doing something to correct your mistakes before you publish (or spend a lot of money on development).

The validity of the question-familiarity-hunch-result aspect of research problems shown by the field-effect transistor can be easily demonstrated by using my selected puzzles and games. The tennis tournament problem is a good example. It is stated as follows: If there are 137 entrants in a tennis tournament, what is the maximum number of matches that may have to be played to decide the winner? The tournament should be scheduled so as to be as fair as possible.

A preliminary hunch, occurring before any real familiarity has developed, is often, "This is obviously a problem for geometric series." A less-frequent hunch is, "Use mathematical induction." A first step is usually to give one player a bye and play a first round of 68 matches, producing 69 survivors for 34 matches and one bye in the second round. When this is all added up, the sum is usually within a few matches of 137.

Then I say, "Use thinking tool 2." (Thinking tool 1 is left as a problem for the reader at this point.) The simplest case, the student usually says, is three players; less often does he say two and only very rarely one. Then thinking tools 3 and 4 lead to a table such as this:

P_o = number of players at start	1	2	3	4	5	...	8
M_T = matches required for tournament	0	1	2	3	4	...	7

Somewhere along the line, the hunch $M_T = P_o - 1$ is stated. I ask: "But is it *always true* that $M_T = P_o - 1$ *no matter* how the byes are scheduled? Will you bet me a dime against a dollar that I can't produce a counterexample?" (This challenge has cost me very little.)

If the decisive hunch that leads to the final ACOR structure has not occurred, I suggest: "Consider the quantity P_E, the number of players eliminated at each stage of the tournament." This quantity is the key attribute of the second scientific thinking tool, and usually recognition that the key postulate is "one match eliminates one player" follows. It is not easy to state this postulate properly; if you doubt this, try to do so before you look ahead at the QLF for Ohm's law or read the footnote.*

The logical structure of the tennis tournament problem is shown in Fig. 5. It is an example of the (key attribute)-(comparison operation)-(result) pattern. This logical structure pattern is harder to get across to students than the principle that the number of matches is one less than the number of players. But it *is* the logical structure that clearly displays the conservation or invariance principles. Nonscience college freshmen have enjoyed mastering it. (This conclusion is based on two years of experimentation in teaching mechanics at San Jose State under the direction of W. A. Gong. Professor Gong has organized a program in the six departments of the school of science to utilize on a unified basis the three scientific thinking tools of this section.) Figure 5 contains two key postulates for the problem. (I used a number of similar diagrams in *Electrons and Holes in Semiconductors.* They helped my thinking; but there has been little feedback from readers.) The first postulate is the elimination principle, and the second, in which P_R is remaining (not eliminated) players, is the conservation of people, in this case, players. Step 1 uses a boundary condition postulate so obvious that it is not shown: before the tournament starts $M = 0$ and $P_E = 0$. Step 2 is "substitute equals for equals." Step 3 uses the definition: M_T corresponds to $P_R = 1$.

The tennis tournament and other problems described have been chosen to give the "you can't change it, no matter what you do" feeling characteristic of important scientific and engineering principles. The final principle, $M_T = P_o - 1$, is often grasped before the logic is understood. That is why the student lacks the necessary conviction to risk his dime to get my dollar. The dollar approach, or its equivalent in classroom prestige, dramatizes the power of the logical structure.

Once a bright student has been taken through one or two of these exercises, he can ask leading questions and provoke a fellow student to accomplish the creative search process. The use of a student-teaches-student program has many advantages: It puts the quick learners to work in roles of leadership such as they may well have in later life and it keeps them active at solving the real problem of imparting knowledge to a colleague. It overcomes the "convoy" effect in which the speed is determined by the slowest by making new tasks available to the fastest. The slower students like the program because they receive personal attention and they need not worry about asking foolish questions of the teacher.

The limited experimentation that has been carried out convinces me of the soundness of the student-teaches-student program, but I fear that it will not receive the contract support it deserves. It does not have the glamour of integrated circuits. There is no profit-motivated incentive for contractors to promote such programs as there is for computerized programmed material.

Let me remark that flashy performance on a problem like the tennis tournament problem is far from a sure sign of competence in progressing through a CSP. I have seen a junior high school student get the answer in two minutes; in contrast, I have also succeeded in getting eminent scientists to pore over it for ten minutes or more. Nevertheless, there is no doubt but that the scientists are better able to bring order out of chaos than high school students.

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* The qualified law form should include the *when not* condition to allow for fewer matches in case of default or withdrawal. This rules out "each match eliminates one player" because that is true no matter whether there are defaults or not. The best form I have found is, "It is *always true* that to eliminate a player requires a match *no matter* how many players, how the byes are arranged, how many matches are played simultaneously, *but not if* a player defaults." This postulate is an ACOR structure.

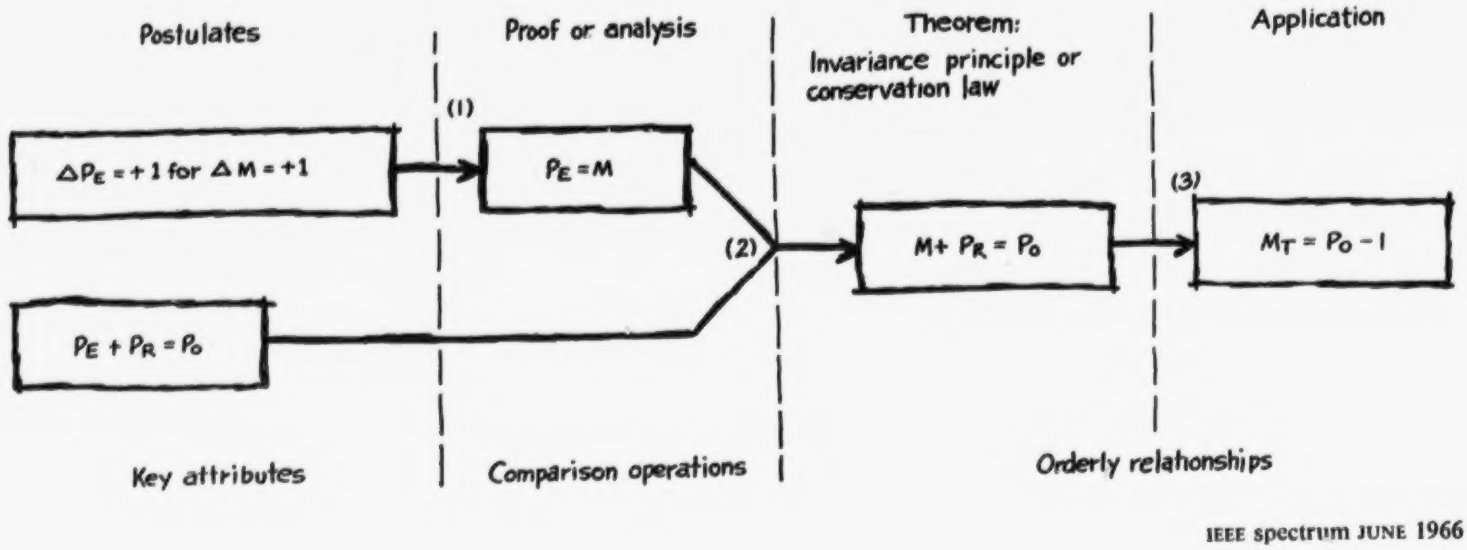

Fig. 5. Outline of the logical structure for the tennis tournament problem.

The scientist's training has conditioned him so that he is convinced that he can solve the silly problem if it's worth his time—and, furthermore, has given him a battery of search thinking tools, such as those discussed in the next section, to search out the order hidden in the chaos. The high school student without luck flounders helplessly, unhappily, and may quit. However, I have seen this behavior improve when the student becomes analytically aware of the realities portrayed by CSP and of the importance of finding how key attributes can be fitted into orderly relationships of the postulate-proof-theorem form.

The separation of one's reasoning into the postulate-proof-theorem form of reasoning shown in Fig. 5 is a form of analytic introspection that is also useful in research and in technical conferences. However, one often encounters a rebuff when one attempts to find out what postulates are actually being used. The questioner is not in the know. He doesn't belong to the club. The articulated science approach is intended to encourage a more constructive and exploratory attitude.

The third scientific thinking tool is the qualified law form,[2] which was illustrated in the footnote to the tennis tournament problem. In science, QLF is particularly important in stressing that most laws have both wide ranges of application and at the same time serious limitations. An example is Ohm's law:

(*What* is true)	It is *always true** that for a two-terminal electronic conductor with majority carriers only, V/I is constant,
(*When* it's true)	*no matter* whether holes or electrons are involved or if ac or dc conditions prevail,
(*When not* true)	*but not if*† the power furnished alters the specimen temperature or the field is high enough to produce hot-carrier effects or the frequency is high enough that a displacement current is comparable to a conduction current or if collision times are comparable to the ac period.

The main feature brought out by this example is not perfection of statement but emphasis on three aspects: (1) *what* it says—a useful relationship is stated; (2) *when* it is practical—you can use it in many circumstances; and (3) *when not* applicable—it does have its limitations.

The qualified law form gives the perspective lacking in the usual definitions of a law of science: "an established fact," "a universal truth."

Before discussing the remaining tool on our list, the ACOR pattern, the role of the search thinking tools in Fig. 3 will be explained.

Search thinking tools and frustration

One of the objectives of the articulated science approach is to increase general awareness of the power of useful principles and of rational reasoning in everyday life.

At present, teaching of postulate-proof-theorem logical structures is largely confined to geometry. However, new-math geometry does not do its best in suggesting how rational reasoning applies to real life. For geometry the postulates now selected in modern mathematics are characterized by mathematical neatness rather than correspondence to objective experimental reality. This basis for selection of postulates inhibits transfer of the postulate-proof-theorem structure to real life. It loses the advantage of Euclid's appeal to the realities of rulers and stretched strings. I fear that the emphasis on mathematical nicety rather than relationship to everyday phenomena may be analogous to the suppression of phonetics a decade ago. We may develop Roberts who can't reason about space just as we had Johnnies who couldn't read.

As an example of the lack of connection between mathematics and reality in present-day education, I recently had a well-above-average graduate student in electrical engineering who argued that we can't really prove that space is three dimensional. He argued that this was only a matter of definition. He now knows more about Bridgman's operational definitions and I use his "bum hunch" as another thinking tool. I also point out how the anecdote about his difficulties with the reality of three dimensions for space helps much as did my bum hunch about the field-effect transistor. As further evidence of the lack of tight connection between various parts of mathematics that I observe from my experience, I estimate that not as many as ten percent of superior high school seniors can easily prove Pythagoras' theorem or prove that $A = \pi r^2$ can be derived from $C = 2\pi r$; perhaps mathematicians in education consider such mundane matters too elementary to discuss beyond the eighth grade. I think these two particular examples of human ingenuity should be selected for dramatized, exaggerated presentation so that they will always be available to the student. (Here I agree with Steinmetz; they should be taught every year.) These are two items to be considered in my recommendations given later.

The articulated science approach is intended to improve rational reasoning ability both in science and in everyday affairs. This aspect is dramatized by the competitive real-life situations of the "take-away" match games. Students frequently exploit the power that the principles give them by defeating their older siblings after school. (This feature might be explored as a partial remedy for the self-esteem problems of students with underprivileged backgrounds.)

The random, frustrating aspects brought out by the creative search diagram are intended to reduce feelings of inadequacy on the part of students who feel they are not working out problems in the way they are supposed to. I have some hope that this aspect of the new approach might reduce the percentage of mathematics haters.

The search thinking tools on the list are supposed to be of help in getting a student under way. If he understands tools 2, 3, and 4, he will look for simplest cases, use pencil and paper, and try to represent quantitative and logical relations symbolically. By doing so he may pump up, as represented in Fig. 3, some relevant ACOR structure out of his reservoir of experience. By properly associating this ACOR with his familiarity with his problem, he may develop the hunch that leads to washing a new logical structure out of a chaotic situation and into his reservoir, as shown in Fig. 3. In this way he can increase the number of reference patterns in his reservoir.

What in Fig. 3 is search thinking tool no. 1? Perhaps you will think that it is, "define the problem." In the tennis tournament, defining the real problem of relating matches played to eliminated players was most of the result. In alchemy the real problem was not how to make gold, but the meaning of *you can't, no matter what*. Clearly, defining the problem is not your first step. How then can you describe what you should do first?

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* Some semanticists object to modifying *always true* by *but not if*. Prof. Gong and I also considered simply *true* and *indeed true*. Our choice of *always true no matter what* gives a dramatic ring we like. Obviously the merit of the QLF does not depend on exact phrasing.

† Originally,[2] I used *provided* something does *not* happen; *but not if* developed while I was working with ninth graders.

The best word I have found for search thinking tool 1 is *action*. One of my standard actions when I am stuck at an equation while reading a technical paper is simply to copy mechanically the equation that blocks my understanding. In this way I load up my short-term-memory or familiarity bank with details about the equation. The action greatly increases the likelihood of a good hunch that will let me see through the problem.

The ACOR pattern

Our short-term, ready-access memories have limited capacity. Overworking them produces fatigue.

One familiar example is the important, long-distance telephone call with poor transmission. You hold a sentence of incomprehensible syllables in your short-term memory until a key recognizable word gives you the clue and these syllables suddenly click into meaning. Under such circumstances, you can't think effectively. After the conversation ends, you feel that you have overworked some brain machinery; you are tired. (When faced with such a situation, I conserve my energies and get a better circuit; at least if I am phoning in the United States.)

A very similar situation occurs when the communication involves foreign language difficulties.

Awareness overload is the name I propose to describe this effect. I interpret the phenomenon of awareness overload as a demonstration of the interference between two uses of the short-term or immediate-access memory banks. When I am holding uninterpreted sounds in awareness, this interferes with my ability to process concepts effectively. I conjecture that a set of neurons in the brain is being monopolized in trying to find associations between uninterpreted memories of sounds and familiar auditory word memories. They then cannot contribute to finding associations between higher level concepts.

The limitation of capacity shown by this example to store new concepts for ready access leads to a common frustrating teaching experience. You wish to impart to a student a demonstration of how A and B imply C. You impart concept A; then you impart B—but when you try to discuss the relationship that makes A and B lead to C, you find A has gone out of immediate awareness for the student. Concept A is apparently stored more remotely, if at all. By repeated processes both A and B finally become well enough established to be simultaneously available to awareness and the argument can be completed. Before this happens your teaching is blocked by awareness overload.

The familiarity in the creative search pattern of Fig. 3 consists of storing essential attributes of the question in a form in which they are available for quick recall. The hunches then occur by some now-mysterious association process that links them to logical structures previously stored. I like to compare this process to the common experience of trying to remember something particular about a person. You may remember that you liked or disliked him. You may remember that his name had two syllables, even that the first letter was D; then often, in a minute or so, the sound or even the spelling comes back. However, you may recall only part of the name. A hunch is like this partial recall. Often your hunch is vague but sometimes it is very specific about the exact relationship of a feature in the problem to one in a pattern you have stored.

My experiences in talking to lawyers, writers, and theatrical directors have impressed me with the generality of the ACOR and creative search patterns. I illustrate with a quotation from John Barrymore: "I love rehearsals. I hate performances." In terms of CSP, this means that Barrymore loved looking for the key attributes of the emotional states of the characters as portrayed by the playwright. He also enjoyed developing hunches during the comparison operations of the rehearsals and creating the orderly relationship that was the finished performance. This is the ACOR pattern of play production. Subsequent noncreative repetitions were what Barrymore hated.

This ACOR structure can be identified in very diverse situations as can be illustrated by expressing the three following cases in parallel form.

1. The number of eliminated players in a single elimination tennis tournament equals the number of matches played.
2. Potential energy defined as weight times height above the floor is conserved in any rotation of a balance lever.
3. Logical forms with their characteristic properties arise within the operation of inquiry and are concerned with the control of inquiry so that it may yield warranted assertions.

In each of the foregoing examples attention has been focused on a significant attribute of the situation:

1. The number of players eliminated and the number of matches played.
2. The potential energies of each of a set of weights.
3. Statements or propositions and their truth or falseness.

Furthermore, some *comparison operation* among the key attributes has been set up. For example, "Socrates is a man"; "All men are mortal"; therefore "Socrates is mortal" relates three statements.

Potential energies are defined in terms of a standard unit. Others are measured with respect to the standard by a comparison operation consisting of comparing weights and comparing heights and multiplying the ratios. (In fact, "standard unit" plus "comparison operation" is the meaning of physical measurement.)

If the lever rotates, all potential energies change in unison.

If a tennis match is played, one more player is eliminated. Increases in eliminated players are compared with increases in number of matches played.

As a neurological hypothesis I propose that the logical patterns of these three examples may all be stored according to one and the same scheme. Another example is the standard postulate-proof-theorem pattern of formal mathematics. The correspondences are illustrated by Table I.

Hunch development would then proceed as follows: Familiarity consists of storing relevant information about the question at hand in those memory banks available for immediate access. The search thinking tools set up opportunities for one-to-one correspondences to be discovered between features of the new problem and features of some stored logical structure. The "quick" and well-trained mind contains a variety of such patterns and makes associations quickly.

What does it take to do this? Why do some brains produce so many more patents and publications than others? I have proposed that this might be related to the number of concepts that they can interrelate at one time.[11] Can this be controlled by some genetic feature such as size of pyramidal cells or length of axones and dendrites in the cerebral cortex? Do the frontal lobes somehow add coding in classifying tags on stored concepts? A frontal lobotomy apparently prevents creation of new reference patterns although it leaves memories intact. How much can we increase effectiveness of rational reasoning by imparting dramatized, exaggerated patterns of logical structures available for transfer? And how can we measure the increases if we do produce them?

There are difficult but, I conjecture, not impossible problems to attack constructively. Answers may well emerge, as Wooldridge[12] emphasizes, from interaction between electronics and neurology.

Some thinking tools in electrical engineering

Superposition, linearity, and symmetry are thinking tools of great importance in solid-state electronics. Consider the Hall effect problem of Fig. 6(A). One analysis predicted that the Hall voltage between points *A* and *B* of an isotropic Hall effect plate would remain finite as the disk radius went to infinity. Buehler, Pearson, and the writer[13] concluded it would go to zero.

I tried the problem on Polycarp Kusch and he came to the same conclusion, pointing out the similarity to the one-ohm resistor net of Fig. 6(B). If each resistor is one ohm, the ohmmeter will read 0.5 ohm. Obviously Kusch had a relevant ACOR at hand.

Why half an ohm? Superposition of two simple conceptual experiments gives the answer. Let one ampere flow into junction *E* and out at infinity (put a large contact ring at infinity in this conceptual experiment), then by symmetry 0.25 ampere flows through the resistor connecting junction *E* to *F*. Turn off the source to *E* and take 1 ampere out of *F*; again 0.25 ampere flows from *E* to *F*. Superimpose the two cases. The ring at infinity plays no role now; throw it away. The superimposed currents produce 0.5 volt between *E* and *F*. Therefore the ohmmeter reads 0.5 ohm. Q.E.D.

Can you transfer to the Hall effect problem? Put a ring contact at infinity, pass 1 ampere into *C*, and use symmetry. The currents don't go radially; they spiral. However, the equipotentials do not. They are single-valued. They can only be circles. Current into *C* produces no voltage between *A* and *B*. Superimpose and you have the answer.

This obvious fact escaped the author of a paper, the reviewing facilities of his organization, and the referees of a reputable journal. The error was hidden somewhere in the mathematics. To transfer: The author and referees were confused by the complexity of scheduling byes in the tennis tournament or the multiple forces on the rowboat.

I consider that an important and challenging engineering educational problem is to produce a set of dramatized, exaggerated reference patterns of linearity, superposition, and symmetry; of dimensional analysis; and of other selected important electrical engineering topics. Their use might both expedite and improve the output of trained engineers—and so might emphasis on student-teaches-student, especially in so far as the important aspect of communicating results is concerned.

Recommendations for a balanced program

Even a superficial inspection of the recent texts prepared by nationally sponsored programs leads to a discouraging conclusion: Some of them are obviously the minimum retainable residue that would keep a writing committee from violent schism. They yield to the illusion that science has covered so much ground that our only hope is to increase the rate of cramming new information into the students' heads. (See the "Prologue.")

The result is an awareness overload of the intermediate-term memory banks. These intermediate-term memory banks have a time constant of the interval from one final examination to the next and discharge very efficiently thereafter.

The articulated science teaching approach can offset this trend. It can continue to emphasize, year after year, the fundamental verity of the ACOR pattern in the human mind:

1. Some things must be accepted; the important ones are key attributes of the problem at hand. This is the A of ACOR.
2. These attributes must be interrelated by some process of logical operations that the student is sure from experience work to yield warranted assertions. This is the CO of ACOR.
3. The outcome is an orderly relationship that makes thinking easier and recall simpler and more systematic. This is the R of ACOR.

I propose that a major aim of research in science education should be the development and perfection of a significant set of dramatized, exaggerated ACOR patterns. These patterns could then be more easily retained by the student. They would also be available for transfer to aid him both in discovery of new relationships on his own

I. Generalized logical structure pattern—ACOR pattern

Key **A**ttribute	**CO**mparison Operation	Orderly **R**elationship
Players eliminated and matches played	Equal increases per match	Players eliminated, equal matches played
Potential energies, weight times height	Conceptual balanced lever experiments; standard unit of potential energy, comparison with any weight at any height	Conservation of potential energy
Statements and their truth or falseness	Interlocking of parts of statements	Logical forms
Postulates and definitions	Proof; comparison operations among aspects of postulates and definitions	Theorem

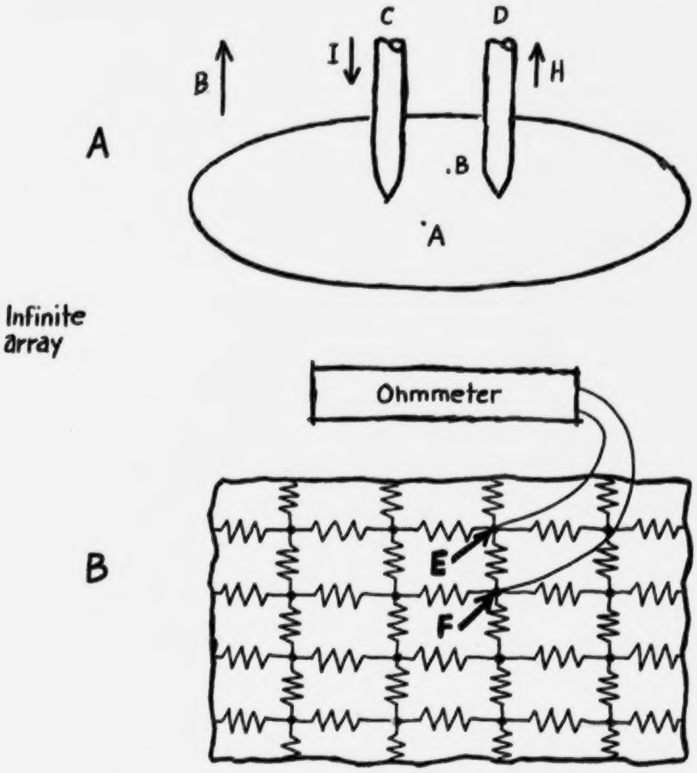

Fig. 6. Example of symmetry and superposition. A—The Buehler-Shockley-Pearson isotropic Hall effect plate. B—The infinite, periodic, two-dimensional square one-ohm resistor net.

and in interpreting scientific principles in his studies.

Our modern educational trend toward a new model of our subject matter each year does not take into account that the human brain is not provably different from what it was 20 000 years ago. (Many now worry that it may be becoming worse, but that is my subject elsewhere.[14-16]) Are we wise to discard Robert the Bruce's spider that showed the value of persistence, the boy who cried wolf, and Euclid? In my opinion, we are not. The educational encyclopedias produced by writing teams are capable of overloading the awareness of any brain save the "idiot savant" who is all memory.

What is the answer? It is selection and *balanced emphasis*. By balanced emphasis I mean: Pick a small, highly selective sample of undeniably important facts and develop optimum exaggerated, dramatized techniques to impart these well. Do these patterns right. Treat superficially all the remaining wonderful variety of accomplishments of modern science and show them as a survey.

I feel it is practical to surmount the objections that no agreed-upon set of first-priority scientific principles can be found. The linearity, superposition examples given in the preceding section are a small existence proof. Slater's detailed balance pattern is another example. With detailed balance a high school student can visualize how a catalyst cannot disturb the end state of a chemical reaction. He does not have to repeat incomprehensible generalized concepts, for example: "Net reaction stops when equilibrium is reached—our operational definition of equilibrium. This must mean that the reaction tendency, called free energy (ΔF), is zero." The fact that Avogadro's number is the number of molecules in 18 unit volumes of water (i.e., cubic centimeters) is the significant factor, not that "a mol is 6.03×10^{23} particles of any kind... atoms... or even people, dollars, or calories." Any trace of an ACOR pattern in this statement is imperceptible. If you think the mol is understood, ask a high school honor student what to change to make a mol 48.24×10^{23}.

Balanced emphasis is my expression for ideas similar to those covered by the "posthole" method or "islands of knowledge." Whatever it is called, developing exaggerated, dramatized, or in any event unmistakably emphasized, experiences on specially selected specific topics will give the student a chance to know what it is to master a logical orderly relationship. By contrast, the survey of the rest of the field of science will show him how vast and exciting is the field of things he has admired from an intellectual distance. And he will know the difference.

This I think is vitally important: He will be able to understand the difference between knowing well on the one hand, and on the other, knowing superficially enough to know the vocabulary and the general purposes but not the tight relationships. With this knowledge the student can have the mental tools to decide better what he wants to do, to know how to do it and when he has done it.

Unrealistic? I, with many others, once worked for three years on a device that one of my colleagues said should be called a "persistor," if it ever became practical!

This material was prepared for the 37th Memorial Steinmetz Lecture 1966 at Union College. It was also presented at the Seventh (1966) National Creativity Conference and at the Second (1966) International Symposium on Communications Theory and Research. Portions of this work were supported by Office of Education Contract OE 4-10-216, Project S-090.

Editor's note: A treatment of "mechanics" incorporating the articulated science teaching approach described in this article is being prepared by Dr. Shockley, with W. A. Gong, for publication in September in the Merrill Physical Science Series, published by Charles E. Merrill Books, Columbus, Ohio.

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F. Research Results Obtained by Application of the CSP Methodology

Several new logical structures related to scientific thinking and to new scientific results in electromagnetic theory have been developed in connection with the principal investigator's participation in this project.

In the science-teaching area, a new concept has been embodied in the term "concept distillation." This expression is intended to convey the same thought as the phrase "articulated science teaching" used in Section E by emphasizing the distillation of the essence of the conservation and invariance principles of basic laws of science. These logical structures are then transferred to the science-oriented subject matter of center of gravity, laws of levers, etc., as discussed in Chapter 2.

One important contribution to concept distillation has been the discovery of a basic invariance principle that has been incorporated in four booklets discussed in Chapter 2. This is the invariant odd-even sequence, namely, whole numbers are alternately even and odd.

The appreciation of the odd-even principle is an example of the focus upon simplest cases also developed significantly in connection with the teaching approach. The concept of "the simplest example of conservation of energy" was a surprising logical discovery that underlies the treatment of energy in the teaching material developed. The interested reader will find a complete analysis of this topic in the Shockley-Gong Mechanics book.*

The principal investigator has had three specific research experiences since developing the research approaches formalized in the Mechanics book. As discussed below, these experiences constitute evidence that conscious application of the research methods of the creative search pattern (CSP) and search thinking tools actually do work.

It should be noted, of course, that the principal investigator has been an extensive publisher of research results since obtaining his doctoral degree at the Massachusetts Institute of Technology in 1936. Some of the methods and viewpoints developed in the Mechanics book reflect the results of this research experience. Thus it could be concluded that his deliberate application of the methods of approach taught with the CSP are simply those natural for him as an effective research worker and that his experience is no evidence that these methods have any general merit. However, the introspective analysis that the principal investigator has made of the research examples described below convinces him to a considerable degree that the methods proposed in this study are not only an accurate description of his own research processes but are also, in fact, generally applicable valid rules for guiding research.

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*William Shockley and Walter A. Gong, Mechanics, Merrill Physical Science Series, Charles E. Merrill Books, Inc., Columbus, Ohio, 1966, page 172.

In the following paragraphs these experiences are described in the first person since this makes the presentation grammatically simpler.

"Hidden Momentum" in Electromagnetic Theory

During the summer of 1966, I initiated a course for 10 new employees at Bell Telephone Laboratories. These individuals were at the Laboratories for the summer and were subsequently leaving, with Bell support, for one year to obtain master's degrees at Stanford University.

In the course of this study I obtained preliminary copies of the Mechanics book and also drew illustrations from electromagnetic theory. One of these illustrations involved a discovery that a key attribute of a certain mechanics problem was the momentum in an electromagnetic field. The particular example I chose was one involving angular momentum discussed in the Feynman lectures on Physics.* This example involves a form of geometry that does not lend itself to ready integration so as to obtain the relevant quantities in simple, analytic form.

I endeavored to improve this problem for pedagogical purposes by finding an analogous problem having much simpler geometry in accordance with the "try simplest cases" search thinking tool used in the CSP diagram. This attempt led to a problem which was sufficiently simple that it suggested applying the considerations not only to a vacuum space but to a space in which the electromagnetic momentum was being carried in matter which had both electrical and magnetic properties different from vacuum.

An attempt to work out the simplest-case results for magnetic material led to a contradiction in electromagnetic theory which had apparently not been fully realized before. I gave the problem of working out some of the details to a graduate student and he and I jointly published the results of our investigations in Physical Review Letters* under the title, "'Try Simplest Cases'--Discovery of 'Hidden Momentum' Forces on 'Magnetic Currents'."

Forces on Electric Currents Flowing through Magnetized Matter

The "hidden momentum" investigations published by Shockley and James led to considering forces acting on currents passing through magnetized material. This turned out to be an obscure and confused subject in which various published references are incorrect. In order to become oriented to this material, I deliberately applied the pencil and paper technique to acquire familiarity. As a purely mechanical operation I forced myself to copy equations from what appeared to me to be the most physically insightful text available on the relevant magnetic theory, namely, the book entitled Electromagnetic Fields and Interactions, vol. I, by Richard Becker and Fritz Sauter, published by Blaisdell Publishing Co., New York, in 1964. (This "action" search thinking tool is discussed more fully under the Dirac Equation research discussed below.) These effects led me to become acquainted with branches of electromagnetic theory which I had only partially understood as an undergraduate student at California Institute of Technology and as a graduate student at Massachusetts Institute of Technology. It is my conviction that my grasp of this material was obtained more rapidly as a result of introspective analysis and actual awareness of the need for storing in the short-term memory banks a number of relevant facts pertaining to theoretical relationships.

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*W. Shockley and R. P. James, Physical Review Letters, vol. 18, no. 20, 15 May 1967, pp. 876-879.

Quite important in obtaining insight in this work was the deliberate selection and use of simplest cases, a feature that I find generally lacking in most of the electromagnetic textbooks. Usually the authors endeavor to produce completely general results with the consequence that frequently the ideas are so fuzzy that they may actually contain incorrect physical interpretation when applied to specific cases.

In this connection I may remark in passing that one of the useful single examples of simplest cases was a current-carrying wire that is permanently magnetized with the direction of magnetization perpendicular to the long axis of the wire. If this wire exists in free space with no external magnetic fields produced save those by the wire itself, then a question is raised as to whether the current and, consequently, the wire will feel a force due to the passage of this current in the magnetic field of the wire. Furthermore, the question arises as to whether the force corresponds to what is known as the H field or the B field. Understanding of this particular "simplest-cases" example was very helpful in obtaining general perspective in this problem.

The result was an unambiguous reinterpretation of the forces on currents flowing in magnetic fields which I presented as a paper at the meeting of the National Academy of Sciences in October 1967.*

Hidden Momentum in the Dirac Relativistic Equation

In the early fall of 1966, I endeavored to apply the creative search pattern technique to a problem in theoretical physics. This problem originated in the "hidden momentum" problem described earlier and published in the Shockley-James letter in Physical Review Letters.

The Dirac equation is probably the most sophisticated mathematical tool that I have ever used in my research work. I was almost entirely unfamiliar with it before engaging in the research effort of the fall

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*Abstract in Science, W. Shockley, "Force in Momentum for Magnetized Bodies," October 27, 1967, vol. 158, p. 535. (National Academy of Sciences meeting, 23-25 Oct 1967, Ann Arbor, Mich.)

To sum up, I evaluate my experience as an existence proof that the methods of the *creative search pattern* and the *search thinking tools* are actually sound for research at a reasonably high theoretical physics level.

NOTE ADDED TO PROOF

A paper entitled "'Hidden Linear Momentum' Related to the $\vec{\alpha}\cdot\vec{E}$ Term for a Dirac-Electron Wave-Packet in an Electric Field" was published in the February 12, 1968 issue of *Physical Review Letters*, a journal "containing short communications dealing with important new discoveries ~~on~~ or topics of high current interest in rapidly changing fields of research..." About six weeks elapsed between submission of the paper and rejection by a referee, transmitted to me on November 6, 1967. I replied on December 18 pointing out errors in the referee's review and making minor revisions. The letter was then accepted for publication on January 18.

This sequence constitutes evidence that the research accomplished has been classified as an "important new discovery." The field is not one of "high current interest"; in fact, the referee in his rejection wrote: "The whole furor over the 'new,' previously unknown or unnoticed contribution to the electromagnetic momentum involving magnetization density puzzles this referee. The treatment...etc....is dealt with in the standard works...." This quotation indicates that the general community of physicists lacks appreciation of the basic problem discovered by the "try simplest cases" approach discussed under "Hidden Momentum" on page 32 of this report.

In early February 1968 I carried out a similar research experiment in respect to an attempt to understand the relativistic electromagnetic energy-momentum tensor. The correct form for this tensor has been a subject of debate and confusion for nearly sixty years. Such famous physicists as Nobel Laureates Einstein, Pauli, and Tamm have commented upon or tried to resolve this confusion.* The debate between two forms for momentum density is well reviewed by Møller. The "hidden momentum" of my own research is related to this controversy. Accordingly, I attacked the energy-momentum tensor problem in February 1968. By deliberate application of the "search thinking tools" and at last by the "try simplest cases," I obtained during a consecutive five-day period an insight apparently previously missing. I anticipate that a definitive scientific publication will result from this effort.

For both the Dirac equation research and the energy-momentum tensor research, I dated and retained all scratch paper used and prepared a running commentary. I would be prepared to make this material available under appropriate conditions for research on these examples of research.

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*For a review of relevant history see the following:

1. C. Møller, *The Theory of Relativity*, Oxford at the Clarendon Press, 1952 (reprinted 1966), pp. 204-206.
2. Albert Einstein, *The Meaning of Relativity*, 5th ed., Princeton University, Princeton, N.J., 1955, pp. 49-50.
3. Wolfgang Pauli, *The Theory of Relativity*, Pergamon Press, New York, 1958, Sec. 35.

Chapter 2

THE INSTRUCTIONAL PROCESS

A. Materials and Equipment

The materials developed in the Shockley Science Education Project consist of 10 instructional units in booklet form. These units are based upon (1) a selection of games and puzzles, and (2) the logical structure of scientific laws in theoretical science. The titles of the booklets are:

Standard Reference Patterns

1. Take 1 or 3 Game
2. Two Coin Problem
3. Two King Problem
4. Odd-Evenness in Nature: the Mirror Problem
5. The Checkerboard Puzzle
6. Competitive Games: Two Pile and Take One through Five

Theoretical Science

7. Center of Gravity
8. Moments
9. Test Your Understanding: CG and Moments
10. Potential Energy

Preliminary forms of several additional units were developed but are not included in this report. They included Tennis Tournament and Take 1 or 4, as Standard Reference Patterns, and, in the Theoretical Science category, Archimedes' Principle and Generalized Energy.

B. Teaching Schedule

The Standard Reference Patterns are taught for a period of about 4 weeks beginning with odd-even problems to illustrate the invariance principle. This is followed with instruction on more complex games and puzzles, emphasizing the nature of conservation laws. Then the student is confronted with competitive game situations requiring him to apply his knowledge about logical structures and thinking.

The next step in instruction, lasting about 8 weeks, seeks to have the student transfer the logical content and intellectual processes learned from the games to quantitative theoretical science. The scientific content deals with a logical structure in mechanics and relates center of gravity, moments, and potential energy. This entire logical structure of scientific laws is based primarily upon two key attributes: weight and length; these are easily quantified by most junior high school science students.

The scope and sequence of the content changed during the three experimental trials (fall, spring, and summer 1966-67). In the first experimental trial the Standard Reference Patterns were alternated with the Theoretical Science units. This was done because the teachers and their students were not sure that the games represented science. In the second experimental trial the teachers attempted to relate conventional science materials and the patterns of scientific thinking taught by the games. Teachers used their "favorite lessons" and attempted to relate these to the words and ideas of the Standard Reference Patterns. The third experimental trial began with teachers selecting five "favorite lessons," using these to introduce the scientific thinking patterns. The teachers were permitted to select their own sequence of games as they saw fit in order to adjust to the needs of their students. Teachers of slower classes were encouraged to proceed at a reduced pace and had the option of omitting certain materials.

C. Characteristics of the Instructional Units

In each of the instructional units students are involved in a continuous pattern of learning about invariance principles (stated as acors and QLFs) and scientific thinking (stated as CSP and STT).* The general strategy is to use certain mental processes (STT) to associate important past knowledge (acor and QLF) with the present search for new knowledge (CSP). These learning skills are explicitly taught to teachers and students. A large magnetic board is used in each classroom to show how past acors, as part of a "memory reservoir," are "pumped" by the proper use of STT to the present CSP. The results are new acors that become part of the memory reservoir, and the process of learning new acors is repeated. See Figure 2-1.

To illustrate how each instructional unit is designed to incorporate both the invariance principle and scientific thinking sought as course objectives, the teaching process for one of the game booklets and one theoretical science booklet is outlined in detail.

The Two-Coin Problem

The Two-Coin booklet is divided into 10 sections, each section representing a major teaching activity. The quotations are from the booklet.

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*These abbreviations are defined as follows:
acor = attribute - comparison operation - orderly relationship;
QLF = Qualified Law Form; CSP = Creative Search Pattern; and
STT = Search Thinking Tool.

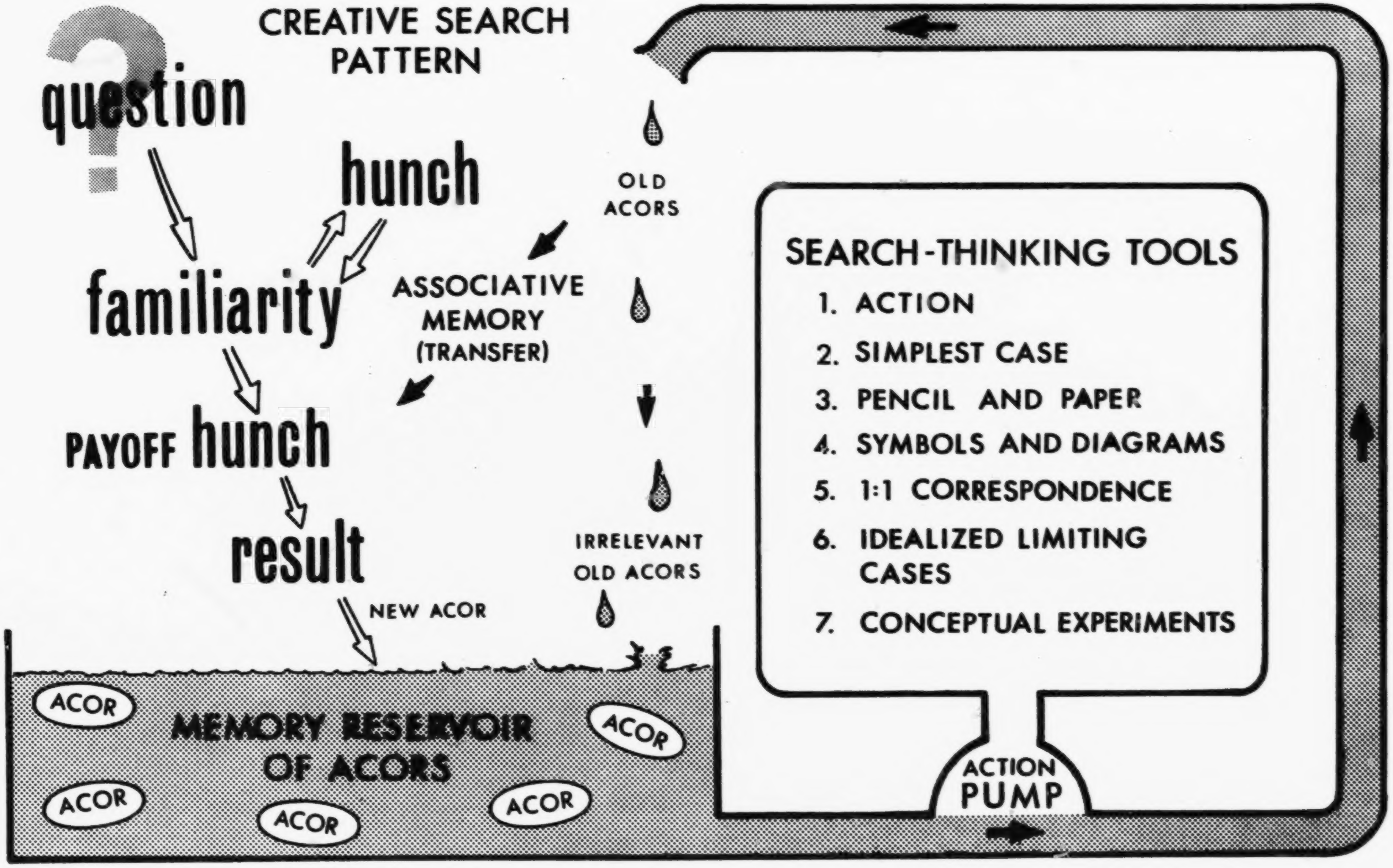
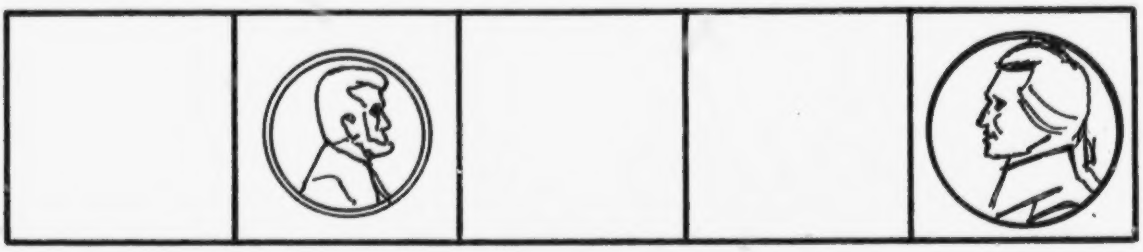

CREATIVE SEARCH PATTERN
question
familiarity
hunch
PAYOFF hunch
result
NEW ACOR
ASSOCIATIVE MEMORY (TRANSFER)
OLD ACORS
IRRELEVANT OLD ACORS
MEMORY RESERVOIR OF ACORS
ACOR
ACOR
ACOR
ACOR
ACOR
ACOR
SEARCH-THINKING TOOLS
1. ACTION
2. SIMPLEST CASE
3. PENCIL AND PAPER
4. SYMBOLS AND DIAGRAMS
5. 1:1 CORRESPONDENCE
6. IDEALIZED LIMITING CASES
7. CONCEPTUAL EXPERIMENTS
ACTION PUMP

Figure 2-1. SHOCKLEY-GONG SCIENCE THINKING DIAGRAM.

1. In the first section the two-coin problem is introduced to the student in the following way:

> This problem is one that you can solve on your own. You will need one strip of paper with five squares and two coins, a penny and a nickel. The figure shows the two coins lying heads up on the five-square strip at the start of the problem. The penny is on the second square from the left, and the nickel is on the far right-hand square.



> The problem is to get both coins both heads up or tails up at the same time, on the same square, while obeying two rules:
>
> (1) You must move a coin only one square at a time.
>
> (2) You must turn the coin over each time you move it.
>
> The order in which you move the coins does not matter. (For example, you may move the nickel several times before you move the penny. You do not have to move the penny, then the nickel, then the penny, in turn.) Also, you may move both coins onto the same square, even if they are not both heads or both tails. (For example, the nickel may be placed on top of the penny.) So remember that any moves are allowed, as long as you obey the two rules.
>
> Can you move the two coins to get them both heads up or tails up on the same square?

2. The student is encouraged to solve the problem on his own and to state the reasons for his conclusions.

3. The student is shown how symbols and diagrams can be used as search thinking tools to find an invariant result.

WHAT	It is always true that in the five-square, two-coin problem you can't place the nickel and the penny heads or both tails up on the same square,
WHEN	no matter the number of times or the sequence you turn the coins over, or what square you try to get both coins on,
WHEN NOT	but not if you disobey the rules (e.g., you do not turn a coin over when it is moved to an adjacent square).

4. The Two-Coin problem is extended to include 137 squares. The Qualified Law Form cannot be applied with certainty to the more general case. The student is challenged to seek a more basic solution to the problem.

5. He is asked to prepare a case to be presented in class, like a lawyer in court, that proves beyond "any reasonable doubt" his conclusions. Key attributes are gathered about a coin, the number of the squares, and the Two-Coin problem.

6. The student compares his case with the following proof based upon this basic invariance principle:

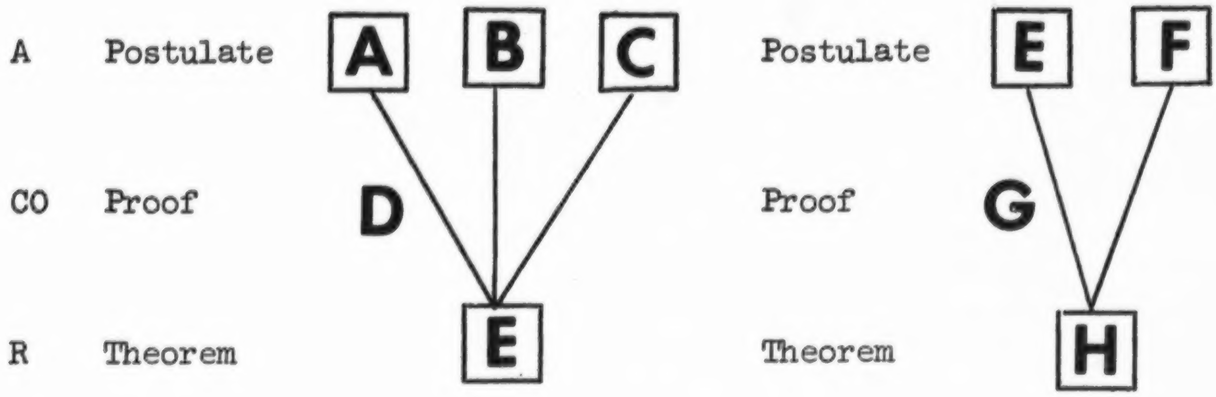
WHAT	It is always true that a coin will have one side up on odd squares and its other side up on even squares, so after every two moves the coin is back to the same side and same type of square as it had at the start,
WHEN	no matter whether you start the coin heads or tails on an odd or even square, or whether you move the coin any number of times to any adjacent square,
WHEN NOT	but not if you do not move the coin one square each time, or you do not turn the coin over each time it is moved.

When this fundamental invariance principle is used as the key postulate for explaining the Two-Coin problem, the following proof is made:

> If the rules of the Two-Coin problem are obeyed, a coin will always have one side up on odd squares and the other side up on even squares (postulate). This particular problem requires that the penny must start heads on an even square, and the nickel must start heads on an odd square (postulate). By combining the two postulates, for this problem, it follows that the penny will always be heads on odd and tails on even, and the nickel will always be heads on even and tails on odd (proof). We must conclude that the two coins can never have the same side up and be on the same square (theorem).

7. A diagram is used to analyze the logical acor structure of the proof.

> The logical proof just presented has three parts, and to stress this idea, we will call logical proofs by the special name of Postulate-Proof-Theorem, or simply PPT. So that you can become more familiar with this kind of proof, we will define, discuss, and diagram the parts of the PPT as shown on the following page.



8. The student is asked to memorize the acor of the Two-Coin problem and teach it to someone else. He is given a set of cards with statements of the Postulates, Proof, and Theorems to help him do this.

9. The student then reviews the Two-Coin problem by retracing his thinking process ("Thinking About Scientific Thinking") in the following manner:

a. The first thing you did was to gain detailed familiarity by reading the description of the problem and by actually trying to answer the question.

b. You soon had the hunch that the problem could not be solved, no matter what. When you used symbols and diagrams, you showed as a result that the five-square problem was impossible to solve.

c. But what if there were 137 squares? This new question required a proof for the Two-Coin problem for any number of squares.

d. A search for the significant attributes of the problem produced two key postulates. This discovery, the most significant of your search, probably occurred when you actually took the penny and turned it over and over, and when you labeled the strip and looked at the odd and even sequence of the numbers of the squares.

e. You were given an opportunity to combine these two invariant sequences in a logical proof.

f. A logical proof was presented in the style of the Postulate-Proof-Theorem.

g. The PPT was further discussed and diagrammed.

h. Finally, you practiced teaching the PPT. You tried to prove to another person, in a convincing manner, why the Two-Coin problem could not be solved.

10. The student tests his understanding by applying his knowledge of the acors of the Two-Coin problem to new problems.

Moments

The Moments booklet is an example of how the invariance principle and scientific thinking taught in the games are applied to theoretical science.

1. The instructional unit begins with a conceptual experiment of a frozen elephant suspended from its tail. The student is asked "Why does this or any freely suspended object return to a point directly below the point of suspension?" An answer is sought using the simplest case of an 8 by 8 inch card freely suspended at different positions from a nail.

2. Next, the student uses a cardboard tipboard as the experimental equipment. He investigates what happens when two sets of objects are placed on the tipboard balanced in stable equilibrium in the following manner. One student places a stack of three pennies anywhere on the tipboard, and a second student tries to rebalance the tipboard by placing, say, a stack of two pennies on it. When a student can win these games of "two stacks," he is asked to state the acor law that enables him to control the tipboard.

3. He compares his law statement with the following word statements and mathematical equation: $W_AD_A = W_BD_B$ (in number of standard weight × distance units). The use of symbols and diagrams as a powerful search thinking tool is stressed.

4. The two players continue with a game of "three stacks." One player places two stacks of pennies anywhere on the tipboard, and the second player tries to balance it with a third stack of pennies. An insight into the attribute "moment" will enable a player to easily control the game. When this occurs, he is asked to summarize his acor as a mathematical equation.

5. He compares his mathematical equation with the following acor written as a "qualified equation" for any number of objects on a balanced tipboard:

$$\Sigma M = 0 \text{ (in number of standard moment units)}$$

that is, moments are "conaddians": they are conserved whenever the objects are in balance; they can be added like numbers; and they are invariant attributes of nature.

6. The newly discovered Law of Moments ($\Sigma M = 0$) is subjected to four experimental tests to determine when the law is true and when it is not true. The student conducts new experiments to determine what happens when: the number of objects is increased, the cardboard fish is used as the tipboard, the center of gravity (CG) of the tipboard is displaced from its axis of rotation, and the tipboard is balanced in a vertical instead of a horizontal plane. During these investigations

the student "weighs" the cardboard fish by three different methods. Also, the attribute "moment arm" is conceived by the student for the first time.

7. These experimental results are summarized in a Qualified Law Form, such as the one below:

WHAT	It is always true that $\Sigma M = 0$ (in number of standard moment units),
WHEN	no matter the material, shape, or size of the objects, the number and measured values of the weights or their positions with respect to the axis of rotation, and direction of the axis of rotation, or the location of the CG of the lever with respect to the axis of rotation,
WHEN NOT	but not if the total weight of an object is not concentrated at its CG, or its moment arm is not a horizontal distance from the axis of rotation.

8. A fundamental definition of the attribute moment is now possible. Moment is defined in terms of a vector force and a moment arm.

9. The attribute moment is measured. The Logical Structure of Measurement is described as an acor:

A	Attribute	Identify the attribute to be measured. Select a standard unit of the attribute.
CO	Comparison operation	Determine the number of standard units contained in the attribute to be measured.
R	Result	Relate the measured values of the key attribute in an orderly relationship, or result.

10. The "intellectual journey" outlined by the Moments booklet is reviewed by the student by "Thinking About Scientific Thinking." Twenty steps of the intellectual journey are outlined and diagrammed on a Creative Search Diagram. The student is asked to communicate his scientific results and thinking to another student. He is given cutout cards to help reconstruct the instructional steps.

D. Equipment for Experiments

The experimental equipment required for the units is minimal. The cost of one complete set, with the exception of the special "balanced rotated lever" demonstration device, is less than $3.00 when made by the teacher or students. A list of the equipment follows; for a more detailed description see the booklets.

1. Mirrors (Odd-Even: Mirror Problem)
2. Wire cage (Center of Gravity)
3. Tipboard (Moments)
4. Soda-Straw Balance (Potential Energy)
5. Balanced Rotated Lever (Potential Energy)

Chapter 3

IN-SERVICE EDUCATION OF TEACHERS

The education of teachers for the Stanford-Shockley Project was under the direction of Dr. Walter Gong, Professor of Natural Sciences, San Jose State College (San Jose, California). The following programs of teacher education were conducted between February 1966 and August 1967.

1. Spring Seminars (1966)

Seven junior high school science teachers from the Palo Alto Unified School District completed an introductory series of 14 weekly 2-1/2 hour seminars. Instruction stressed scientific thinking and logical structures by the use of games, puzzles, and the conservation of energy unit (Fig. 3-1). Teachers had opportunities to practice with the new materials to gain experience in the teaching style required by the Stanford-Shockley program (Fig. 3-2).

2. Summer Writing and Development Program (1966)

Five of the science teachers who completed the spring seminars (1966) were involved in an 8 week program at Wilbur Junior High School to rewrite the Shockley materials for ninth grade science. Professor Gong was assisted in this program by Dr. Fred Holmstrom and Dr. Jean Fetter of the San Jose State College Physics Department and two university science students who had studied the materials under Dr. Shockley at Stanford University. About 100 ninth grade students were used to help evaluate the preliminary materials. These materials were taught to them and their feedback was used to revise subsequent rewrites.

3. Fall Teaching and Supervision (1966)

Six teachers who completed the spring seminars (five of whom had also participated in the summer program) taught the experimental curriculum materials in three Palo Alto junior high schools during the fall semester, 1966. Professor Gong, assisted by two other teachers, made fourteen 1-hour weekly classroom visits to each of the six participating teachers. During these visits the experimental teachers reported their experiences in teaching the Shockley materials. Note was made of their comments, which were used to revise future teaching practices.

4. Spring Semester Saturday Seminars (1967)

Five teachers who completed the 1966 fall experimental teaching trials helped to train six other science teachers in the new materials. These teachers were from the Carlmont, San Carlos, and Andrew Hill High Schools. Professor Gong supervised these sessions, assisted by Professor Edith Selberg from the Science Education Department at San Jose State College, and Clyde Parrish, an associate of the Shockley Project.

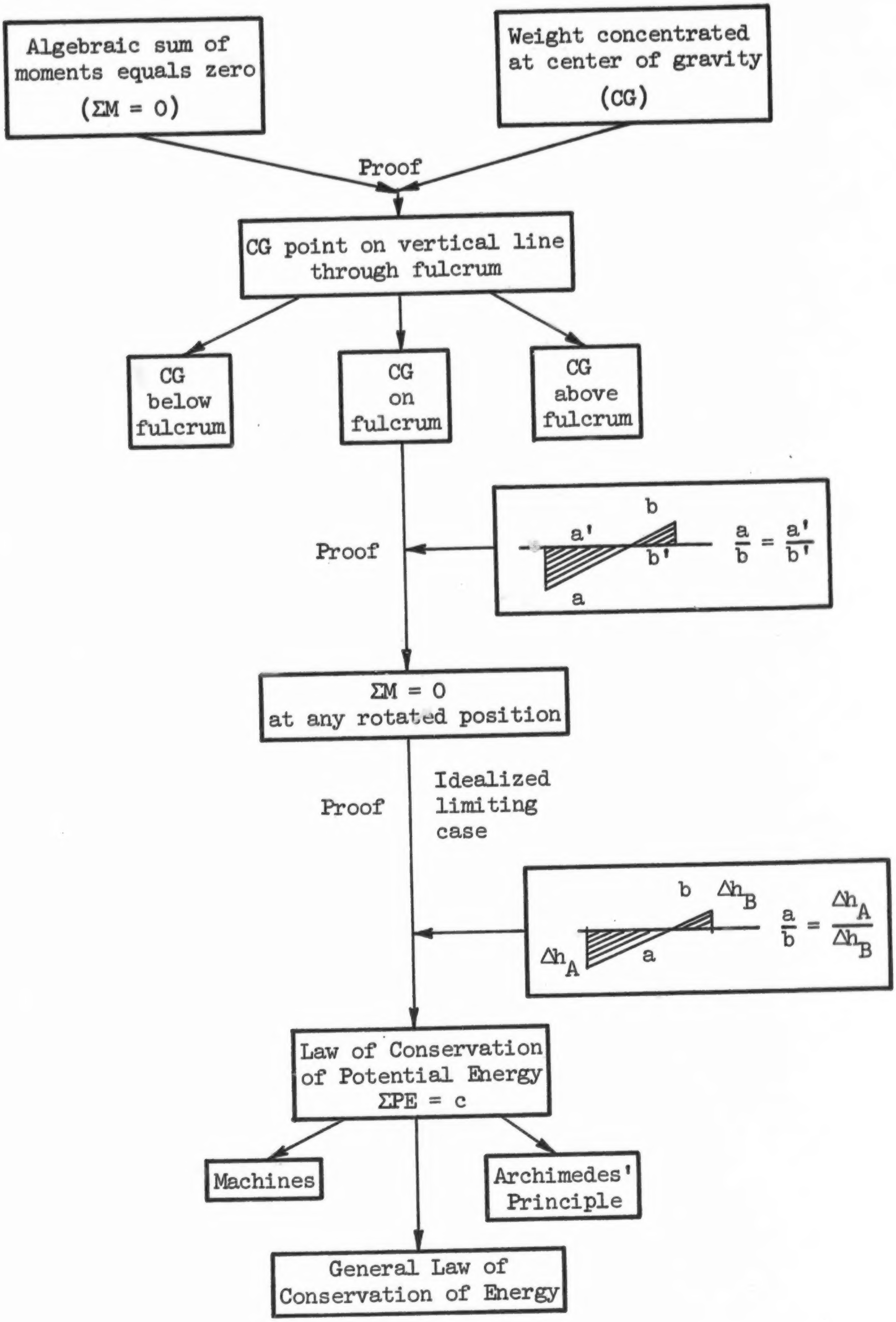

Algebraic sum of moments equals zero
(ΣM = 0)
Weight concentrated at center of gravity
(CG)
Proof
CG point on vertical line through fulcrum
CG below fulcrum
CG on fulcrum
CG above fulcrum
Proof
b
a'
b'
a
a/b = a'/b'
ΣM = 0 at any rotated position
Proof
Idealized limiting case
b
Δh_B
Δh_A
a
a/b = Δh_A/Δh_B
Law of Conservation of Potential Energy ΣPE = c
Machines
Archimedes' Principle
General Law of Conservation of Energy

Figure 3-1. A LOGICAL STRUCTURE OF LAWS LEADING TO THE GENERAL LAW OF CONSERVATION OF ENERGY. Taught to science teachers in the Stanford-Shockley Project.

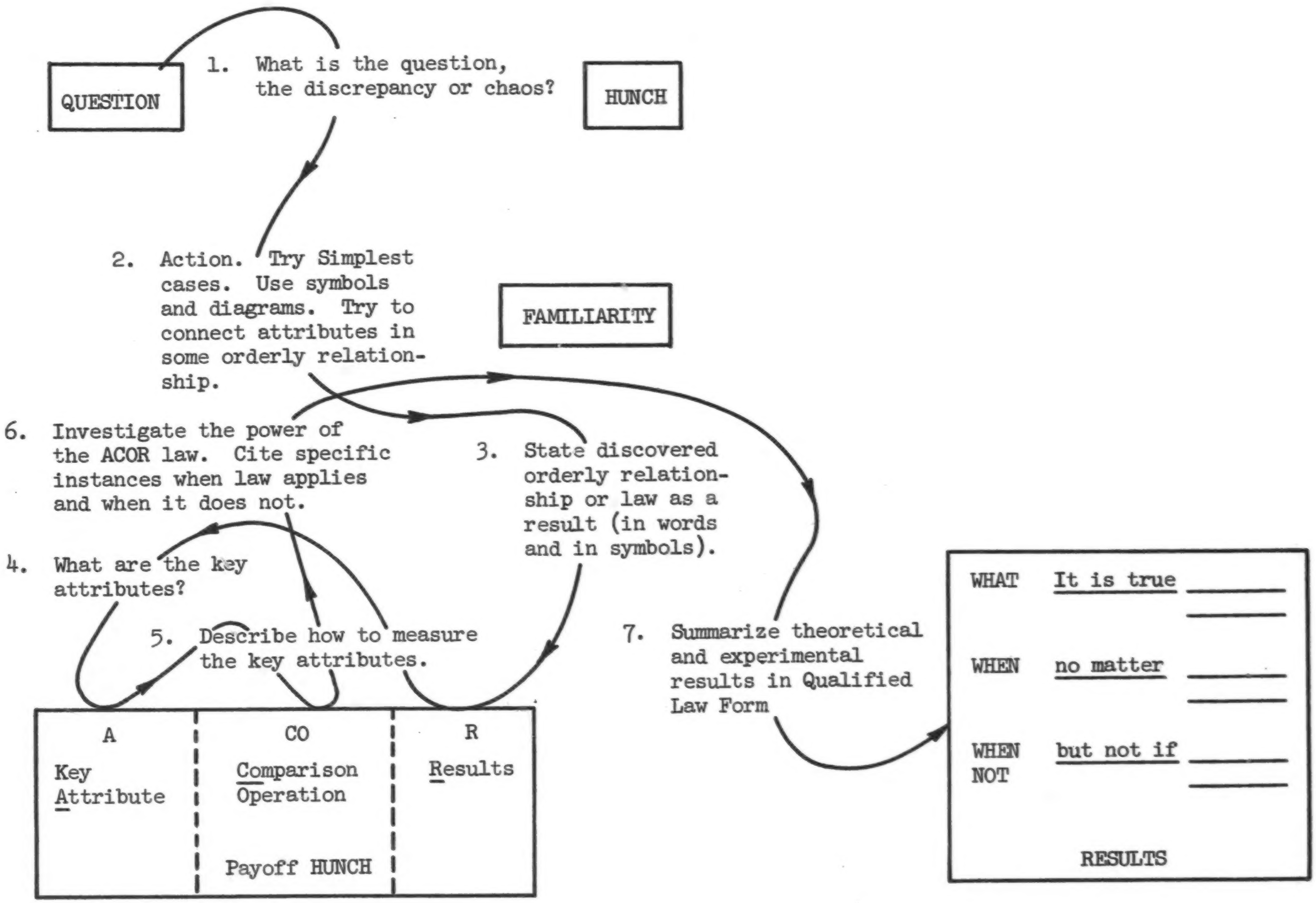

QUESTION
1. What is the question, the discrepancy or chaos?
HUNCH
2. Action. Try Simplest cases. Use symbols and diagrams. Try to connect attributes in some orderly relationship.
FAMILIARITY
6. Investigate the power of the ACOR law. Cite specific instances when law applies and when it does not.
3. State discovered orderly relationship or law as a result (in words and in symbols).
4. What are the key attributes?
5. Describe how to measure the key attributes.
7. Summarize theoretical and experimental results in Qualified Law Form
A
Key Attribute
CO
Comparison Operation
Payoff HUNCH
R
Results
WHAT It is true
WHEN no matter
WHEN NOT but not if
RESULTS

Figure 3-2. AN EXAMPLE OF THE NEW TEACHING STYLE OUTLINED IN A CREATIVE SEARCH DIAGRAM. This is but one of an almost infinite number of possible teaching patterns and sequences.

5. Summer Session Wilbur Junior High School Experiment (1967)

Two experimental classes at Wilbur Junior High School were taught the units of the new materials for a 6 week period during the summer of 1967. In addition, Professor Gong, assisted by Dr. Holmstrom and two science teachers, worked on improving teaching techniques and the writing of supplementary instructional materials.

6. San Jose State College Workshop for Science Teachers (1967)

A 2 week summer workshop (see Fig. 3-3) was conducted at San Jose State College, June 19-30, 1967, in terms of the following objectives:

a. To train science teachers to use a new "Strategy for Teaching Science," that is, the Shockley materials;

b. To acquaint science teachers with the inquiry processes, logical structure, and applications of scientific laws and theories appropriate to the Shockley materials; and

c. To provide science instructors with practice in using the new units.

Thirty-four elementary and high school science teachers and supervisors met daily from 9:00 a.m. to 3:00 p.m. to participate in the program. The following topics were treated in the course:

Recent Curriculum Trends and Experiments in Science Education

Case Studies in History and Philosophy of Science

Examples of Scientific Thinking in Games and Theoretical Science

Demonstrations of the New Teaching Strategy

Practice Teaching in the Use of the New Techniques

Applications of the New Strategy and Use of Mental Tools in Science

Instruction was conducted by the following:

Dr. Fred Holmstrom, Workshop Director and Chairman Physics Department, San Jose State College

Dr. Walter Gong, Assistant Director, Shockley-Stanford Project, San Jose State College

Miss Edith Selberg, Natural Science Department, San Jose State College

Mark Bunge, Physical Science Department, San Jose City College

Joseph Beard, Instructor, Stanford University, School of Education

	FIRST WEEK
June 19	PURPOSE OF WORKSHOP PRETESTS Rational Reasoning Z Nature of Science X-3 Problem-Solving Inventory Y Raven Progressive Matrices Test Plan and Performance Test A CASE STUDY IN HISTORY AND PHILOSOPHY OF SCIENCE 1. Atmospheric Pressure
June 20	RECENT TRENDS IN SCIENCE EDUCATION CASE STUDY IN HISTORY AND PHILOSOPHY OF SCIENCE 2. Motion 3. Atomic Theory 4. Life
June 21	SCIENTIFIC REFERENCE PATTERNS A model for teaching discovery, test, and extension of scientific concepts, laws, and theories. The Teaching Model illustrated by simplified examples: 5. 2-Coin 6. 2-King 7. Take 1 or 3 8. Geometrical Optics 9. "Coke Bottle" experiment 10. "Black Box" experiment
June 22	SCIENTIFIC REFERENCE PATTERNS The Teaching Model illustrated by simplified examples: 11. Checkerboard Puzzle 12. Tennis Tournament 13. Center of Gravity 14. Moments
June 23	SCIENTIFIC REFERENCE PATTERNS The Teaching Model illustrated by simplified examples: 15. Potential Energy 16. Archimedes' Principle 17. Law of Conservation of Energy 18. Other Conservation Laws
	SECOND WEEK
June 26-28	PRACTICE TEACHING OF SCIENTIFIC REFERENCE PATTERNS A. Teachers teach scientific reference patterns to teachers. B. Teachers teach scientific reference patterns to students. C. Teachers teach scientific reference patterns for television video tape.
June 29	APPLICATION OF SCIENTIFIC REFERENCE PATTERNS Teachers discuss and make lesson plans of other teaching units in terms of scientific reference pattern.
June 30	POST-TESTS Rational Reasoning W-1 Nature of Science Inventory X-3 Problem-Solving Inventory Y Raven Progressive Matrices Test Plan and Performance Test B SUMMARY AND EVALUATION
	(June 19-30, 1967)

Figure 3-3. SHOCKLEY-STANFORD - SAN JOSE STATE SCIENCE TEACHER WORKSHOP TEACHING SCHEDULE.

Guest lecturers at the Workshop were:

Dr. William Shockley, Director, Stanford-Shockley Project, Stanford University

Dr. Paul Hurd, Professor of Education, Stanford University

Dr. Clifford Schmidt, Biology Department, San Jose State College

Dr. Charles Bell, Biology Department, San Jose State College

Thus six programs of teacher education on the rationale, development, and use of the Shockley instructional materials were a part of the Stanford-Shockley Project. These programs were used primarily to gather useful information for the refinement of instructional materials and to identify problems associated with the introduction of new science instructional materials involving a major change in teaching style.

A sampling of the teacher comments gathered at the end of the Summer Workshop, 1967, is presented in Section 4C.

Chapter 4

DATA ANALYSIS

The evaluation of the Shockley program was made in three phases. In the first phase, fall 1966, the program was tested in 10 classes in Palo Alto. This phase had two functions: (1) to develop test instruments; (2) to try out the procedures and materials of the program.

In the second phase, spring 1967, the program was tested again in 10 classes which were matched on ability level. The purposes of this testing were the same as those of the first phase.

The third phase, summer 1967, was a controlled experimental evaluation of the program. Tests had been developed which appeared to measure the direct effects of the program; other tests had been chosen to measure related and expected effects. By this time, procedures had been well developed and teachers thoroughly trained.

The results of the evaluation in these phases are reported consecutively in the following pages. The tests developed for this program are described first since they will be referred to throughout the report of the evaluation results.

A. Test Instruments

The following published tests* were used in the project:

SCAT (School and College Ability Tests)

Standard Progressive Matrices, Sets A through E

Advanced Progressive Matrices, Set II

Differential Aptitude Test, Abstract Reasoning subtest

BSCS Processes of Science Test--"The concerns of the authors were with the methodology of science; the bases for judging facts, principles, and concepts..." (from the Manual prepared by Biological Sciences Curriculum Study and published by the Psychological Corporation, New York). 40 multiple-choice items.

Tests used in the Biological Sciences program, the Introduction to Physical Science (IPS) program, and the Earth Sciences Curriculum Project (ESCP) were made available for use in the experimental evaluation conducted during the summer of 1967. Publishers were reluctant to release these tests as they were still in the developmental stage. Reliability and validity data were not available; norms were available for the test used in the Earth Sciences Curriculum project.

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*The first four types of tests are described more fully in Oscar Krisen Buros (ed.), "The Sixth Mental Measurements Yearbook," The Gryphon Press, Highland Park, N.J., 1965.

Although aware of the limitations of these tests, we reasoned as follows. The BSCS test has been constructed to measure ability to think scientifically and does not test for isolated items of scientific information. Each of the other tests does measure specific items of information related to the content of their respective curricula; but they also contain a number of problems which might be reasoned out with the information contained in the problem and some general scientific concepts likely to be known to junior high school students. Therefore, if the Shockley program has improved students' ability to think, it might reasonably be expected that they would do better on these tests than if they had not had the Shockley program. We did not expect them to be superior to students who had had the programs related to the tests, with the possible exception of the BSCS test; but if they performed as well, it would be some evidence of the extent to which the Shockley training might generalize.

Reliability figures are not reported here because they were not available from the publisher. We did not compute them, reasoning as follows. If the results of comparisons showed the Shockley group to have performed as well or better than other groups, then we would compute the reliability estimates since the treatment would have to be quite powerful to have produced an effect if the measures were unreliable. However, significant effects favoring the Shockley group did not occur; the results were what is usually found with achievement. Further analysis of these tests seemed pointless.

Although it is preferable to use tests of known reliability and validity, tests with these characteristics which also measure the complex cognitive effects expected to be produced in the Shockley program do not exist. We used as many tests as possible that had desirable psychometric characteristics, such as the Abstract Reasoning Test. We also used the science achievement measures in hopes of detecting any changes in these complex behaviors.

In addition to the tests described above, new test instruments were developed to measure the achievement of certain unique objectives of the project. These are described separately below.

Rational Reasoning Tests

The commonly used reasoning tests employ the following three conventions:

1. Each examinee is exposed to exactly the same set of test items.
2. Each item is expected to be worked on for a relatively short period of time, usually a minute or less.

3. Each item is assumed to be independent in the sense that exposure to its content will not be of any specific help in answering some other item on the test (it may be of help in acquainting the examinee with the item format).

The first of these conventions provides convenience in administration and scoring; the second and third conventions enable one to obtain a relatively large number of responses from each examinee over a wide range of content. It should be kept in mind, however, that these are arbitrary conventions and that further progress in test development may result from considering alternatives to these three conventions. For example, there has been recent interest in computerized testing from the point of view of efficiency: the examinee's answers can be used to direct him to a set of items of intermediate difficulty, which will provide more information about him than will items that are too easy or too hard.

The Rational Reasoning Test developed for the project departs from the second and third conventions. It provides information about the examinee's capability for sustained rational reasoning in a kind of situation where the relevant parameters of the problem are not neatly prepackaged and labeled for him. The examinee is first given time to acquaint himself with a problem, the important features and the solution of which he must discover. He then stays with this problem through several stages from initial presentation to solution. These stages can be expressed roughly in one-syllable words as follows:

A level - Can he do it?

B level - If we give him a hint, can he do it?

C level - If we do it for him, does he know that it's been done, and how it's been done?

(The letters indicate an evaluation of the student's ability in the same way that college grades do: A level performance is better than B level performance, which in turn is better than C level performance.) His performance may be scored not merely as to whether he will solve the problem, but also as to how much help he needs to solve it, and as to whether he can apply the solution to other similar problems and recognize those superficially similar problems to which the solution does not apply. Such information is not directly available from more conventional reasoning tests.

Two forms, Z and W-1, of the Rational Reasoning Test were eventually developed. Each form contains two basic problems, for each of which the student is taken through the three stages described above. Forms Z and W-1 are reproduced in the appendix.

Scoring. The two problems of Form W-1 were composed of 30 and 21 separate questions. Problem 1 of Form W-1 contained 5, 15, and 10 separate questions at the first, second, and third stages, respectively, Problem 2 contained 5, 8, and 8 questions at the first, second, and third stages, respectively. One could thus obtain a score for each student at each stage of each problem, or a "stage one" score across problems. Differential weights could also be given to each stage. As will be seen in a later section, however, the simple-minded procedure of merely counting the number of questions answered correctly produced a highly significant difference between experimental and control groups on one major comparison. To investigate whether the superiority of the experimental group was confined to one particular stage of the reasoning process, the following analysis was made: at each stage and substage the proportion of students in each group getting all five questions right was computed. The results are presented in Table 4-1.

Table 4-1

PROPORTIONS OF STUDENTS IN EXPERIMENTAL AND CONTROL GROUPS ANSWERING ALL FIVE QUESTIONS OF EACH STAGE CORRECTLY

	Stage 1	Stage 2a	Stage 2b	Stage 2c	Stage 3a	Stage 3b
Experimental	.39	.65	.41	.33	.65	.71
Control	.21	.56	.22	.14	.49	.57

As can be seen, the superiority of the experimental group was not confined to a particular stage but rather showed itself consistently through all the stages. Accordingly, further analyses of evaluation data used only a simple "total right" score. Perhaps further information could have been extracted from more sophisticated scoring techniques, but this would have diverted too much time and money from the primary purposes of the project.

Reliability. The format of the Rational Reasoning Test, involving nonindependence of items, does not make it reasonable to apply the conventional internal indices of reliability. Estimates of both internal and test-retest reliability were made by intercorrelating total item right scores on Form Z, Problem 1; Form Z, Problem 2; Form W-1, Problem 1; and Form W-1, Problem 2. This was done separately for the experimental and control groups (spring evaluation). The results are presented in Table 4-2.

For each group the internal reliability of Form W-1 (the posttest) is higher (.55; .50) than the internal reliability of Form Z (the pretest), but still sufficiently low to work with separate Problem 1 and Problem 2 posttest subscores in analysis of other data.

Table 4-2

INTERCORRELATIONS AMONG FORMS AND SECTIONS OF THE RATIONAL REASONING TEST

	Experimental Group				Control Group			
	Z(1)	Z(2)	W-1(1)	W-1(2)	Z(1)	Z(2)	W-1(1)	W-1(2)
Z(1)	--	.28	.31	.21	--	.16	.23	.16
Z(2)		--	.30	.32		--	.15	.10
W-1(1)			--	.55			--	.50

Nature of Science Test

The Nature of Science Test was designed to measure understanding of what a scientist's goals are and how he operates. This 12-item inventory is reproduced in the appendix. A crude item analysis of data from the spring evaluation, contrasting the performance of the group of students getting eight or more items right with the performance of the group of students getting three or fewer items right, showed that items 8 and 12 best discriminated between the two groups. Item 8 deals with invariant relationships; item 12 deals with conceptual experiments.

Problem-Solving Inventory

The Problem-Solving Inventory (reproduced in the appendix) was based upon Crutchfield and Covington's Thinking About Thinking Test. It was designed to measure attitudes toward problem solving and thinking.

A crude item analysis of data from the spring evaluation, contrasting the performance of a group of students getting 22 or more of the 26 items right with the performance of students getting 12 or fewer items right, showed that items 7, 19, and 24 best discriminated between the two groups. These three items deal, respectively, with confidence in approaching a problem, knowing how to get started in solving a problem, and willingness to persist in the face of difficulty.

B. Procedure and Results

Evaluation studies were carried out during the fall, spring, and summer (1966-67). Each study contrasted the posttest performance of ninth grade science students in the Shockley-Stanford Science Education Project with that of control students not given that treatment.

Fall Evaluation, 1966

In the fall semester, data were collected on 10 experimental and 9 control classes. Neither students, classes, nor teachers were randomly assigned to treatments. Instead, the existing science classes of those teachers who had some seminar or teaching experience with the project were assigned to the experimental treatment, and other ninth grade science classes in the same school district were roughly matched with them to constitute the control treatment. The basis of matching was the administrative "lane" (Research, A, AB, B, BC, or C, in descending order of ability) of the class.

Two analyses of covariance were carried out using SCAT scores as covariate and the total score on the Rational Reasoning Test, Form Z, as criterion scores. A simple two-group analysis, using the individual student as sampling unit, is shown in Table 4-3. In this analysis the number of students has been used as the N in computing F-values. This is not strictly legitimate since the classes, not students, were assigned randomly to treatments. The consequence of using the number of students as N is to overestimate the significance of F. Since we were trying to detect any differences that might exist, and since a more carefully designed study was being planned, we decided to run the risk of a Type II error. If no significant differences had been found under these conditions, then future plans for evaluation would either have to be revised or abandoned.

Table 4-3

ANALYSIS OF VARIANCE FOR SCORES ON THE RATIONAL REASONING TEST, FORM Z, FOR FALL 1966 EVALUATION

	df	MS	F
Treatment	1	5.3733	--
Error	426	9.8359	

No effect of experimental treatment is evident. A two-way analysis of covariance with experimental treatment and class lane as factors is shown in Table 4-4.

The results of the second analysis, showing a significant difference favoring the experimental group, were encouraging but, in view of the negative results of the first analysis and the crudity of the experimental design, certainly not definitive.

Table 4-4

ANALYSIS OF VARIANCE FOR RATIONAL REASONING SCORES
SEPARATED BY TREATMENT AND ABILITY LEVEL
GROUP OF STUDENTS

	df	MS	F
Treatment	1	61.6086	7.19 ($p < .01$)
Lanes	5	22.6825	2.65 ($p < .05$)
T × L	5	10.1208	1.18
Error	237	8.5727	

Spring Evaluation, 1967

The spring evaluation involved five experimental and five control classes. Again neither students, teachers, nor classes were randomly assigned to treatments. The spring evaluation was distinguished from the fall evaluation by having more experienced teachers for the project classes, and by using revised and improved teaching materials and procedures.

Four analyses of covariance were carried out, with individual students as the sampling unit, SCAT as covariate, and Rational Reasoning Form W-1, Standard Progressive Matrices, Nature of Science, and Problem-Solving Inventory tests as criteria (Table 4-5). Table 4-6 shows the adjusted mean score for each group on each criterion measure.

Table 4-5

ANALYSIS OF VARIANCE OF SCORES FOR SPRING EVALUATION

	df	MS	F
Rational Reasoning Test, Form W-1			
Treatment	1	1527.221	28.33 ($p < .001$)
Error	206	53.902	
Standard Progressive Matrices Test			
Treatment	1	97.182	5.41 ($p < .05$)
Error	198	17.965	
Nature of Science Test			
Treatment	1	38.87	11.57 ($p < .001$)
Error	183	3.36	
Problem-Solving Inventory Test			
Treatment	1	126.75	10.73 ($p < .01$)
Error	183	11.81	

Table 4-6

MEANS OF SPRING EVALUATION SCORES ON RATIONAL REASONING, PROGRESSIVE MATRICES, NATURE OF SCIENCE, AND PROBLEM-SOLVING INVENTORY TESTS

	Experimental	Control
Rational Reasoning	40.409	34.980
Standard Progressive Matrices	51.768	50.337
Nature of Science	5.970	5.054
Problem-Solving Inventory	18.692	17.016

Experimental Test of the Shockley Program, Summer 1967

During the summer of 1967 an experiment was conducted to test the effectiveness of the Shockley program. In contrast to the studies conducted during the preceding fall and spring, this study had the principal characteristics of a true experiment; for example, it was possible to assign students randomly to different programs. By this time, also, the experimental tests had been developed to the point where they were considered sufficiently reliable to provide an adequate assessment of the effects of the program.

The Palo Alto Unified School District regularly offers science programs to summer school students. These students are free to sign up for regular science programs, such as chemistry courses, or for special science programs which, upon completion, satisfy the science unit requirements in the junior high school.

Announcements were made in the spring that three science courses would be available to junior high school students during the summer of 1967. The announcement indicated that enrollment in each course would be limited and that students would be assigned to one of the three but not necessarily to his first choice. Signing up for these programs meant that a student was making himself available to one of the three programs being offered.

The courses offered were the Shockley program, the Introduction to Physical Science program, and the Earth Science program. Each course was taught by experienced teachers who were familiar with the program they taught and were enthusiastic about it. These teachers had experience in teaching science by emphasizing understanding and grasp of basic principles and concepts. They also had highly positive attitudes toward science and the value of science in the development of the individual student.

Characteristics of Children in the Program. Following is a description of the sample of children participating in the project:

> 101 children were randomly assigned to one of the three programs. 50 children (35 girls and 15 boys) were assigned to the Shockley program and 51 children (26 girls and 25 boys) were assigned either to the Introduction to Physical Science program or the Earth Science program.

The mean Scholastic College and Aptitude Test (SCAT) scores for the two groups were:

	Experimental	Control
Boys	62.5	71.4
Girls	67.3	64.3

The Raven Progressive Matrices Test was also administered to all of the students and the mean scores for each group were:

	Experimental	Control
Boys	49.7	51.1
Girls	51.5	51.6

Although the groups do not differ significantly from each other in aptitude, the sample is not a representative sample of Palo Alto Unified School District school children because they are students who, for one reason or another, are attending summer school. However, they are not students who are scholastically deficient. Many parents send their children to summer school as a way of occupying their time. Other children attend summer school in order to free their schedule during the year for additional subjects. Although the group cannot be said to be strictly representative of Palo Alto children, sampling bias was controlled by random assignment and by using aptitude scores as a covariate in statistical analyses.

The children were informed that as part of participating in these science programs they would be tested extensively to assess their understanding of what they were learning. At the beginning of the summer session, all children were administered the Raven Progressive Matrices Test, the Rational Reasoning Test, Form Z, the Nature of Science Test, and the Physical Science Inventory Test. (See Section A for a description of test materials.)

At the conclusion of the summer program, several days were used to administer the posttests. Those administered were the Abstract Reasoning Section of the Differential Aptitude Test, an advanced form of the Raven Matrices Test; the Rational Reasoning Test (with two subtest scores reported here--one for the chess problem and one for the gate problem), the Nature of Science Test, and the Physical Science Inventory. In addition, the tests used in the Earth Science Curriculum Program were administered to all groups; there were parts 1, 2, 3, and 4 of the Introduction to Physical Science Program test, and the Biological Sciences Curriculum Study.* Thus, each group was administered the major criterion test of the program in which it was enrolled and the major criterion instruments for each of the other programs.

The reason for administering all these criterion tests was to determine the extent to which training in any one program might generalize to measures of achievement in the other programs. It was recognized that the content of the ESCP test, the IPS test, and the BSCS test had not been learned by children in the Shockley program. However, these tests did contain problems which might be worked successfully by reasoning about the problem and using some general science information which these children might be presumed to have. The tests used in conjunction with the Introduction to Physical Science program were the tests most heavily loaded with content taught in the program. Children in the IPS and ESCP programs, although not trained in the Shockley program, had teachers who stressed scientific thinking in problem solving. Further, the problems in the Rational Reasoning Test do not depend on specific science knowledge but can be worked correctly by reasoning about the problem. If the other two science programs had developed scientific thinking habits, these children might be expected to perform reasonably well on the Shockley criterion test without specific Shockley training. Thus the criterion measures did provide a means of assessing the effects of each of these programs with respect to reasoning about scientific problems and achievement of specific science content.

Results. The pretests, Raven Progressive Matrices and Rational Reasoning, Form Z, were used as covariates in subsequent analysis of posttest performance. As SCAT test scores were also available for these children, they were also used as a covariate in analysis of covariance tests.

All posttest scores were analyzed by using a general linear model for analysis of variance. This model permits a test of main effects (which in this experiment are treatments), and a test by class and by sex of subject. Since the children did have different teachers, separate analyses were made by classes for a class effect, and since the sex distribution was not balanced across treatments, analyses were made by sex of subject. Interactions among treatments, sex of subject, and class were also tested. Results are reported by posttest with the covariate specified in each instance.

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*Both of these tests have been used in the development of these programs. They were still in developmental form, and are being revised. No reliability and validity data are available on these instruments. Although this information was not available, the tests appeared to have content validity. Whatever unreliability may characterize the instruments would affect the scores of students in all groups in a random fashion. The risk incurred in using the tests would be that "true" differences between groups might not be detected. This risk is worth taking because, if significant differences between groups were found, one would have greater confidence in the results.

Performance on Rational Reasoning Tests. The Rational Reasoning Test had two parts which were analyzed separately: the chess problem and the gate problem. In this analysis the Rational Reasoning, Form Z is used as a covariate. The treatment groups differed significantly on the chess problem (F = 3.85; df = 1,92). (See Table 4-7.) The means and standard deviations for each of the groups separated by sex and class are presented in Table 4-8.

Table 4-7

ANALYSIS OF VARIANCE FOR CHESS PROBLEM SCORES ON THE RATIONAL REASONING TEST

Variable	Residual Sums of Squares	df	F	p
Treatments	2492.12	1,92	8.76	< .01
Sex	2370.71	1,92	3.85	
Treatments by sex	2330.72	1,92	2.23	n.s.
Sex by class	2314.74	2,92	0.79	n.s.

As can be seen, the Shockley groups performed at a higher level on this test with one exception. The differences, although statistically significant, are not numerically large; there is considerable overlap between the groups. There is also consistent sex difference, favoring boys, on this test which appears mainly in the control groups, although, as can be seen, Class 1 in the Shockley treatment shows a marked difference in performance between boys and girls. The difference by sex is approaching statistical significance (F = 3.85; df = 1,92).

No differences appear on the gate problem. Although the Shockley-treatment group does better on one part of the Rational Reasoning Test, its performance is not maintained on the second part.

When SCAT is used as a covariate, a significant difference is obtained by treatments (see Table 4-9), p less than .01 (F = 7.91; df = 1,92). A significant sex difference is also obtained (Table 4-9), p less than .05 (F = 4.12; df = 1,92). Means and standard deviations for the chess problem scores are presented in Table 4-8. When the gate problem scores are analyzed using SCAT as a covariate, no differences are obtained.

Table 4-8

MEANS AND STANDARD DEVIATIONS OF EACH TREATMENT GROUP BY SEX AND CLASS ON CHESS PROBLEM OF THE RATIONAL REASONING TEST

		N	Mean	SD
Shockley Class 1:	Boys	5	24.0	3.7
	Girls	20	21.7	6.1
Shockley Class 2:	Boys	10	24.2	5.8
	Girls	15	24.4	5.4
IPS Class:	Boys	11	23.6	5.4
	Girls	17	19.5	4.8
ESCP Class:	Boys	14	22.6	5.1
	Girls	9	19.0	6.7

Table 4-9

ANALYSIS OF VARIANCE FOR CHESS PROBLEM SCORES ON THE RATIONAL REASONING TEST

Variable	Residual Sums of Squares	df	F	p
Treatments	2163.04	1,92	7.91	< .01
Sex	2081.00	1,92	4.12	< .05
Treatments by sex	1993.82	1,92	0.10	n.s.
Sex by class	2003.45	2,92	0.27	n.s.

Nature of Science Inventory

On the Nature of Science Inventory, using the pretest scores on this test as covariate, the differences approach statistical significance (F = 3.56; df = 1,92). The Shockley groups are consistently superior, though the absolute magnitude of the differences is not large (see Table 4-10). Again, there is considerable overlap among all groups. No sex difference appears on this measure.

Table 4-10

MEANS AND STANDARD DEVIATIONS OF TREATMENT GROUPS ON NATURE OF SCIENCE INVENTORY POSTTEST SCORES

		N	Mean	SD
Shockley Class 1:	Boys	5	5.8	1.6
	Girls	20	6.2	2.0
Shockley Class 2:	Boys	10	6.4	1.0
	Girls	15	6.6	1.7
IPS Class:	Boys	11	5.0	1.7
	Girls	17	5.7	1.7
ESCP Class:	Boys	14	5.4	1.3
	Girls	9	4.9	2.1

Significant treatment differences appear on the Nature of Science tests when SCAT scores are used as a covariate (see Table 4-11), which are well beyond the .01 level (F = 9.21; df = 1,92). The means are the same as those reported in Table 4-10.

Table 4-11

ANALYSIS OF VARIANCE FOR NATURE OF SCIENCE TEST SCORES WITH SCAT SCORES AS COVARIATE

Variable	Residual Sums of Squares	df	F	p
Treatments	268.61	1,92	9.21	< .01
Sex	245.67	1,92	0.58	n.s.
Treatments by sex	244.35	1,92	0.07	n.s.
Sex by class	247.88	2,92	0.70	n.s.

Physical Science Inventory

The difference between the experimental and control groups is statistically significant on this measure, using pretest scores as covariates, beyond the .01 level (F = 7.53; df = 1,92). The means appear in Table 4-12. As can be seen, the means of the Shockley groups are consistently superior to those of the other groups with one exception--boys in the IPS treatment program.

Table 4-12

MEANS AND STANDARD DEVIATIONS OF EACH TREATMENT GROUP BY SEX AND CLASS ON THE PHYSICAL SCIENCE INVENTORY SCORES

		N	Mean	SD
Shockley Class 1:	Boys	5	19.2	3.3
	Girls	20	19.9	3.3
Shockley Class 2:	Boys	10	19.1	4.5
	Girls	15	19.1	3.3
IPS Class:	Boys	11	20.5	2.7
	Girls	17	16.6	3.4
ESCP Class:	Boys	14	18.7	3.3
	Girls	9	16.8	4.4

Earth Science Curriculum Program Criterion Test

Using SCAT scores as a covariate, a significant treatment difference was found (Table 4-13), p less than .05 (F = 4.05; df = 1,92). Similarly, a sex difference is obtained which is significant beyond the .01 level (F = 6.57; df = 1,92). The means are reported in Table 4-14. As can be seen, the class which had the ESCP program performed significantly better than any other group. Interestingly enough, boys in the IPS class do as well as boys in the ESCP treatment. Apparently there is some content in IPS which facilitates performance on ESCP criterion tests. The treatment differences appear to be occurring between the ESCP and IPS classes and the Shockley classes.

Table 4-13

ANALYSIS OF VARIANCE OF EARTH SCIENCE CURRICULUM PROGRAM SCORES WITH SCAT SCORES AS COVARIATE

Variable	Residual Sums of Squares	df	F	p
Treatments	3008.30	1,92	4.05	< .05
Sex	3086.99	1,92	6.57	< .05
Treatments by sex	2889.12	1,92	0.24	n.s.
Sex by class	2927.70	2,92	0.74	n.s.

Table 4-14

MEANS AND STANDARD DEVIATIONS FOR EACH TREATMENT GROUP BY SEX AND BY CLASS FOR ESCP CRITERION SCORES

		N	Mean	SD
Shockley Class 1:	Boys	5	28.6	8.9
	Girls	20	27.9	6.4
Shockley Class 2:	Boys	10	28.9	10.0
	Girls	15	27.1	7.8
IPS Class:	Boys	11	35.3	5.8
	Girls	17	27.6	7.4
ESCP Class:	Boys	14	34.1	8.9
	Girls	9	28.7	8.9

Introduction to Physical Science Criterion Test

Again, a significant treatment difference is found favoring the IPS group on score on the first part of IPS criterion tests, using SCAT scores as covariate (Table 4-15). The significance level is beyond .01 (F = 13.5; df = 1,92). The means are reported in Table 4-16 where it may be seen that the Shockley and the ESCP groups score similarly but both score quite differently from the IPS group.

A similar difference is found on Parts 2 and 3 of the IPS test where the treatment difference is significant beyond the .01 level (F = 8.94; df = 1,92). The differences favor the group which had the IPS treatment (Table 4-17). Note, however, that the absolute level of the scores for all groups has dropped.

Table 4-15

ANALYSIS OF VARIANCE FOR INTRODUCTION TO PHYSICAL SCIENCE TEST SCORES, PART I WITH SCAT SCORES AS COVARIATE

Variable	Residual Sums of Squares	df	F	p
Treatments	937.69	1,92	13.54	< .01
Sex	847.44	1,92	3.38	n.s.
Treatments by sex	819.61	1,92	0.24	n.s.
Sex by class	826.60	2,92	0.52	n.s.

Table 4-16

MEANS AND STANDARD DEVIATIONS FOR EACH TREATMENT GROUP BY SEX AND BY CLASS FOR INTRODUCTION TO PHYSICAL SCIENCE TEST SCORES

		N	Mean	SD
Shockley Class 1:	Boys	5	9.6	2.3
	Girls	20	8.0	2.4
Shockley Class 2:	Boys	10	8.2	3.4
	Girls	15	7.6	2.6
ESCP Class:	Boys	11	9.5	3.9
	Girls	17	8.8	2.4
IPS Class:	Boys	14	14.2	4.6
	Girls	9	11.4	5.7

Table 4-17

MEANS AND STANDARD DEVIATIONS FOR INTRODUCTION TO PHYSICAL SCIENCE, PARTS II AND III SCORES FOR EACH TREATMENT GROUP BY SEX AND BY CLASS

		N	Mean	SD
Shockley Class 1:	Boys	5	7.0	1.6
	Girls	20	6.6	2.0
Shockley Class 2:	Boys	10	6.7	2.0
	Girls	15	6.0	1.7
ESCP Class:	Boys	11	7.4	1.8
	Girls	17	6.6	2.4
IPS Class:	Boys	14	10.2	2.9
	Girls	9	8.0	3.5

Nonsignificant Differences

No differences by treatment or by sex were found for the Abstract Reasoning Test of the Differential Aptitude Test Battery, the advanced form of the Raven Progressive Matrices Test, the BSCS Criterion Test, and the gate problem of the Rational Reasoning Test when SCAT scores were used as the covariate.

Table 4-18 summarizes the differences found for each criterion measure. Items 1 to 9 are achievement tests; items 10 to 12 are measures of attitude toward science and scientific thinking.

Table 4-18

SUMMARY OF RESULTS FOR EACH TEST AND MAJOR EFFECTS*

Test	Covariate	Treatment	Sex
1. Rational Reasoning - Chess	Rational Reasoning Pretest	X(SH)	[X](B)
2. Rational Reasoning - Gate	" "	--	--
3. Rational Reasoning - Chess	SCAT	X(SH)	X(B-C)
4. Rational Reasoning - Gate	SCAT	--	--
5. BSCS Criterion Test	SCAT	--	--
6. ESCP Criterion Test	SCAT	X(ESCP)	X(B)
7. IPS Test, Part I	SCAT	X(IPS)	--
8. IPS Tests, Parts II & III	SCAT	X(IPS)	X(B)
9. IPS Test, Part IV	SCAT	--	--
10. Matrices	Matrices Pretest	--	--
11. Advanced Progressive Matrices	SCAT	--	--
12. Abstract Reasoning Test (DAT)	SCAT	--	X(G)
13. Nature of Science Inventory	Nature of Science Pretest	X(SH)	--
14. Nature of Science Inventory	SCAT	X(SH)	--
15. Physical Science Inventory	Physical Science Inventory Pretest	X(SH)	--
16. Physical Science Inventory	SCAT	X(SH)	X(B-C)

*Treatment by sex and sex by class is not reported because no significant differences are obtained.

NOTES:

1. An "X" indicates an obtained significant difference. When the difference is large but not significant, the "X" is bracketed.
2. The group having larger mean scores is indicated in parentheses: SH, Shockley; ESCP, Earth Science Curriculum Program; IPS, Introduction to Physical Science Program.
3. The sex group with larger mean scores is indicated in parentheses: B, boys; G, girls; B-C, boys control.

C. Reactions to the Program

Several assessments of opinions and feelings about the program were made. These observations had two purposes: (1) to alert the investigators to problems during the program, and (2) to provide some information about teachers' and students' reactions. These purposes were served by gathering the data in the forms described below. No attempt was made to quantify the data precisely or to do statistical tests of significance. Although not highly objective, the results are presented with full awareness of their limitations for summative evaluation.

Fall Experimental Trial, 1966

Professor Edith Selberg interviewed students taught by the 6 teachers of the Shockley program during 15 regular class sessions. Twelve interviews were conducted with small groups of from 2 to 6 pupils, and oral and written responses were obtained from 8 classes.

The students were asked the following questions:

1. What are you learning?

2. How are you learning?

3. What have you learned so far?

4. What parts of the program do you not understand or are giving you trouble?

5. How would you change the course to make it better?

6. What was your idea of science before you entered this course?

7. What does science mean to you now?

8. What do symbols on the chart mean?

The analyses of the information obtained were summarized by Professor Selberg and Clyde Parrish, Administrator of the Project, as follows:

1. For a majority of the students the program expanded their conception of science from a fact-oriented study of existent knowledge to a thinking about problems and the generation of new knowledge. The usual conception of science at the beginning of the course was, "Science is the study of stars and planets" and "Science is experimenting, using equipment, mixing chemicals, dissecting animals." After two months of instruction, 55 of the 73 students who answered the question, "What does science mean to you now?" stated one of the following:

Science is: solving a problem
asking questions
testing and thinking
reasoning things out
logic and how things are proved
a study of measurement
a logical study of things to find answers
thinking
like mathematics
learning how to learn

2. Almost every student interviewed replied that he had improved in at least one new thinking skill. For example, the 73 students who responded to the question, "What have you learned so far?" listed 26 kinds of behavior dealing with cognitive skills. A partial list follows:

Ask questions.
Write what I learn.
Work out my problems faster.
Take more time to think through my work.
Write a Qualified Law Form.
Find more answers.
Think logically.
Establish order in my problem situations.
Make use of a hunch.
Make a postulate-proof-theorem faster.
Write the search pattern I use.
Concentrate on one specific thing to find out about it.
Do not take things for granted.
Require examples before I believe something.
Read the problem several times so I know what to do.

It was observed that the self-use of these cognitive skills was being effectively taught in certain classes, while in other classes opportunities for students to use the skills on their own were practically absent.

3. One-third of the students indicated that the contents and the time spent on instruction were highly satisfactory to them. The strongest endorsements were usually made by the higher ability students: "It's keen," "I don't think it should be changed." All interviewed groups recommended better ways to introduce the units, to develop the meaning of the words, to extend learning, to provide for individual differences, and to teach the contents.

4. Most high-ability students had developed an operational meaning of the vocabulary of the program, using such words as acor, postulate, attribute, theorem, law. The lowest ability students during this period were not certain or did not understand the meaning of these key ideas stated as vocabulary words.

In addition to the interviews conducted by Professor Selberg, the six teachers who were teaching the Shockley program for the first time were asked the question, "What has the program done for the students?" Three typical responses were:

> It has given them a way of dealing with problems. Most important, it has given them a framework which is universal for science. The students can now take a series of facts and put them in a logical structure, which then allows them to make some basic transfers. This has always been the basic goal of education. (Alvares)
>
> I am not sure that this course will pay dividends immediately for the student. I am sure, however, that it will give them new tools, new patterns, and a more orderly relationship in their approach to solving problems. (Rayner)
>
> That difficult concepts don't necessarily come easy. That they should not give up on a problem which seems unsolvable but use what they have learned in previous problems to help them with their new problems. That science involves the quantifying of important key attributes. They learn the material well enough so that they can teach it to another person. (McRae)

Summer Experimental Trial, 1967

Two experimental trials later, in July 1967, the 27 students of one of the experimental classes (Flesher) were asked to answer the question: "Suppose I had a magic instrument that could measure the greatest changes about you as a result of this course. What would the instrument measure about you?" Every one of the 27 stated that the greatest changes were cognitive in nature. A partial list of typical student responses includes the following statements:

I don't realize it, but I automatically arrange my thoughts according to the Creative Search Pattern.

I became aware of a thought process; I have begun thinking about thinking. I think I will be able to apply the concepts I've learned to many subjects.

After I was presented with a problem I automatically went through the CSP and applied old acors.

Format for attacking any problem the rest of my life.

I just learned how to think in a logical way.

Know how to go about finding results from chaos.

The way I think. By helping me get out of the bum hunches and into the payoff hunch. Help me solve things quicker.

When I get a problem now I try to find an attribute, while before I just hoped someone would tell me the answer.

Changed how I thought.

One month later, in August, this question was included in a questionnaire administered to the two experimental and two control classes: "How much did this summer's science course, compared to other courses you have taken, teach you how to think about new ideas and problems? Check one choice." The results were as follows:

Choices	Experimental	Control
More than any other course in my life	20	2
More than most courses	29	23
About the same as other courses	5	25
Less than other courses	--	--

It was interesting to note from the responses on the same questionnaire that about the same proportion of experimental and control students stated about the same degree of "liking" science, and the two groups also considered with about equal value that science was the "best preparation for leading a good life."

Summer San Jose State College Workshop, 1967

At the end of the Workshop, the following statements were presented to the teacher participants:

Several of you have asked whether this Workshop can be continued after summer. Signify one of the three levels of personal commitment. Remember, once you write your level of commitment, you must follow through with it.

Level 1: I will participate in teaching and developing Shockley materials next year, no matter how much difficulty I encounter or how preliminary the materials. The Shockley Project will tell me what to do.

Level 2: I will participate in selected topics, but I will control the instruction, not the Shockley Project.

Level 3: I do not wish to teach or be involved with the Shockley Project next year.

Every one of the 34 participants signified in writing or by a show of hands that they would attend another Shockley workshop or extension course offered by San Jose State College, provided there were no conflicts in schedule. Sixteen teachers chose commitment level 1, 12 chose level 2, no one chose level 3. No responses were received from six teachers (some were absent, others were doing something else at the time). This opinion poll was not meant to be exhaustive, but the trend appears obvious.

Typical comments made by each participant are listed below. (Note that no response was received from participants 1, 3, 5, 9, 13, and 26.)

Commitment Level 1

2. I am willing to work with program, no matter problems, criticisms, etc. However I would like more background, if possible. Perhaps a year long workshop to share ideas and problems with others.

6. I will work with the program for sure...no matter what. My school district will support the program.

10. I am willing to work with the program next summer as well as during the next year, scholastic year.

    I like very much you get in touch with us through offering a course, one session a week that we do not lose contact with you.

12. Will try as much as I can for the equipment I can make or find, no matter problems, criticisms, etc.

14. Work with program, no matter problems, criticisms, etc.

    I am anxious to try the creative search pattern on my students.

15. My choice (definite) - I am inclined toward #1, but would need to check (with my principal).

16. I would like to work with the program no matter what; however implementation in Physiology will be the stumbling block.

18. Work with program, selected topics, you in control.

19. I personally would be willing to go the "full boat." All of us teaching freshman science at Hill will be working to individualize instruction using Health Science as a medium. Our plans to date are to do Health Sci. 1st semester and Shockley-Gong 2nd semester. The decision ultimately rests with the group. The group consists of Dick Smith, Jay Russell, Bill Gilmore, and myself.

21. I would like to commit myself wholeheartedly to the program, however, I must also have the commitment of my district that I may do so no matter how much material is lost, stolen, or broken. I do not anticipate any problems from my school district.

    Mrs. Hartsell and I plan to work closely together in utilizing this program.

22. Work with program in case of selected topics (you in control).

24. Work with program, selected topics, you in control.

30. I would like to use the program to the fullest extent of its present development starting in September at the eighth grade level--one semester class two times per year, 100-200 students per semester depending on participation of team teacher.

    I would especially like to work on development of new materials and future text writing revision, etc., especially if you hold BSCS style summer writing conferences.

31. Work with program, no matter problems, criticism, etc.

    I have used a lab-type course based upon observation for several years so this program will fit my needs and beliefs very well.

32. Work with program--no matter what.

    I teach this way anyway and have always written or selected materials that are an active science approach. I know that these materials would challenge my students (7th and 8th). It is different than their K-6 "Science." It also allows them to tackle "why" which is difficult to do.

I would like to be included in writing some units--especially in chemistry-physics for 7th and 8th grade level. I have been working on a series of lessons measuring change that has been a favorite. I would like to rewrite it into this approach.

My principal allows me to do the things I feel necessary to teach science and tries to obtain proper $. I can make some of the materials at home in my own shop, also.

33. As the sci. consultant to the district, I commit the entire district. We are waiting for you to contact us. I have discussed this with the Supt. and he says, "let's go."

Commitment Level 2

4. Next school year I will be teaching 1 period of PSSC physics (which is totally under my control) and 4 periods of Harvard Project Physics (which is still in the experimental stages and I am committed pretty much to their program and control). As it is possible, I would like to bring in your ideas in the PSSC. I feel considerably less freedom to formally include outside material in the HPP.

7. Work with selected topics, teacher in control.

8. Selected topics and modified.

11. I am committed next year in a (last year and next year) development program of Inquiry program--textbook Interaction of Matter and Energy by Adams, Chainey.

I like your program very much. I have gained a lot and would like another summer course. (The best I have ever taken.)

I will be using your principles in lesson planning and especially in evaluation of the program I am working in. Your concepts, ideas, and laws are a must for good teaching.

17. Work with program on selected topics. Would like to meet with group in the future.

20. I am interested in the structure of the directing pattern of learning, formally and constantly referred to. The best use of the program to me is to reinforce the elements of this way of bringing about learning by reinforcement of process and summarization.

I am convinced that without the terminology I teach for the learning objectives hoped for here.

I intend to transfer the pattern to slow, or unsuccessful learners in basic mathematics.

23. Work with program, selected topics, me in control.

I would like to try it to the point where I and the students have a good feel with the process. Then I'd like to establish it on a somewhat regular basis (once or twice a week). I would also like to be informed on how the program is progressing; what new ideas, materials, changes, etc.

25. Work with program, selected topics, me in control.

27. Work with program--selected topics.

28. Level 2.

29. I plan to work on the program with SELECTED AREAS--SELECTED ACTIVITIES. My program next year calls for all Biology teaching. I will integrate the Shockley-Gong method as well as I can into BSCS Green VERSION.

Our district has a 1 semester physical science requirement at the 9th grade level. We have tried the ESCP and are working with the Princeton Project (TSM) and may try IPS. I intend to pass as much of this program as I can on to the instructors involved in the courses. I certainly believe much of this material and method can be incorporated.

34. Work with program, selected topics.

Chapter 5

CONCLUSIONS

The major results of this study can be summarized under the following headings: (1) intellectual effects of the Shockley program; (2) achievement effects of the Shockley program; (3) attitudinal effects of the program; and (4) reactions of teachers and students.

It will be recalled that two kinds of major tests of this program were made. First, the program was tried out in a number of classes during the regular academic year. The conclusions of this study favored the Shockley program; that is, students performed significantly better on four tests: the Rational Reasoning Test, Form W-1, the Standard Progressive Matrices Test, the Nature of Science Test, and the Problem-Solving Inventory Test. The mean differences between experimental and control groups substantially favored the Shockley program group on the Rational Reasoning Test. Significant, but small, differences were obtained between the means of the experimental and control groups on the Matrices, Nature of Science, and the Problem-Solving Inventory tests.

The second test, the experimental study that was performed in the summer of 1967, was regarded as a more critical test of the effects of the program for the following reasons: (1) the study met more of the requirements for drawing valid inferences about the Shockley program, and (2) a wider range of criterion tests was used to assess multiple effects of the program. Unfortunately, the results of this experiment did not correspond as closely to those of the evaluation studies made during the regular year as one would have hoped.

A. Intellectual Effects

One of the questions raised in this study was whether or not the Shockley program produced significant changes in intellectual skills which would be reflected in improved performance on measures of intellectual aptitudes. The Standard Progressive Matrices Test and the Abstract Reasoning Test of the Differential Aptitude Test Battery were used to measure these changes. In the spring evaluation study, significant differences were found on the Matrices Test which were not confirmed in the experimental evaluation of the summer. The Abstract Reasoning Test in the summer evaluation produced a sex difference favoring girls, but not favoring the treatments, nor was there a treatment by sex interaction. The only reasonable conclusion seems to be that this program does not produce substantial effects which are detectable on standard measures of intellectual aptitude.

B. Achievement Effects

The major effects were assessed by using the Rational Reasoning Test in the spring evaluation study, and another form of this same test in the summer study, together with the BSCS Criterion Test, the Earth Science Program Criterion Test, and the Introduction to Physical Science Test. The attempt here was to determine if the Shockley program produced skills which would generalize to problem solving in areas where the students had not had the formal content associated with those areas. The fall (1966) study did not provide a direct answer to this question, but the summer (1967) study did.

In both the fall and the summer studies, Shockley groups performed in a significantly superior way on the Rational Reasoning Test; however, as the summer study indicated, this superiority was on the first part of this test (the chess problem). The Shockley group showed no superiority on other science achievement measures. The summer test indicated that performance on a specific science achievement test was correlated with having had formal course work on the content of that test.

It seems reasonable to conclude that the superiority of the Shockley training program is best demonstrated on criterion instruments which measure the kinds of intellectual skills for which the program trains. It does not produce any facilitative effect on standardized achievement measures which are heavily dependent upon the content of a subject area. It should not be concluded that the students in the Shockley training program might not perform in a superior manner in these other areas if the tests contained problems which place greater demand upon their intellectual skills rather than on recall of specific content. However, claims for a wide generalization of ability to areas other than that in which they have been trained cannot, with the present evidence, be supported for students who have had the Shockley training program.

C. Attitudinal Changes

One of the major purposes of the Shockley program was to produce positive attitudes toward scientific thinking and problem solving. It is clear from the results of both the spring and summer evaluation studies that such changes do occur. Shockley students perform in a superior manner on the Nature of Science Inventory and the Problem-Solving Inventory in both studies (spring and summer).

It can be safely concluded that the program does produce some significant shifts in attitude, although the extent to which these shifts are permanent cannot be determined since we did no testing beyond the time limits of the actual studies themselves. However, it is reasonable to assume that if these changes are relatively permanent, they may have some long-term effects on achievement in science.

D. Reactions of Teachers and Students

It is clear that students and teachers alike were generally positive toward the Shockley program. Nevertheless, it would be unwise to assume that this program could be introduced without meeting some teacher resistance. For example, the induction of a teacher into this program requires such extensive training that sometimes, in the initial phases of this training, considerable resistance is met. Undoubtedly, there are teachers who either could not learn how to teach science in terms of the Shockley approach, or who would strongly resist learning to do so for a variety of reasons. However, when teachers persist through the training period, and when they have had some experience with the program itself, they are enthusiastic in their attitudes about both the changes in their students and the changes in themselves.

Students are generally positive, though there are some who do not think that this program represents "science." This attitude is more related to what they have learned to think of as science than to characteristics of the Shockley program itself. Data gathered on the students indicate that they do feel positive about the experience, and that they feel that the program has had some significant effect on their ability to think.

Again, the long-term effects have not been assessed; but it is a positive sign that students react favorably and feel that the training is making some significant difference in their lives.

The subjectivity of both of these evaluation reports should be noted. At best, they represent a positive support for this innovation. They do not demonstrate that the Shockley program has had other significant effects. But, in introducing changes in curricula, an important consideration is the attitudes of both the teachers who mediate the change and the students who are involved in it.

E. Discussion

Although every effort was made to give the Shockley program a fair test, some of its limitations must be recognized. First, the Shockley program is relatively short and occupies only a relatively small proportion of any science program. Whether or not its overall effect can be expected to be permanent or substantial, given the limitation in amount of exposure to the training, is a moot point. Such data as are here presented are mixed. When large numbers of students were used in a relatively uncontrolled study (subjects were not randomly assigned to groups), some strong evidence appeared that Shockley groups did substantially better on a number of limited criteria. On the other hand, a tighter study did not produce significant results under significant conditions when optimally they should have appeared.

Given a time limitation in a regular curriculum, one would expect the effects to be attenuated; but it is under these circumstances that some effects seem to emerge, or at least the probability of their occurring seems likely. The most reasonable conclusion from the data presented here is to assume that minimal effects occurred. However, whether more substantial results would occur with greater time investment would remain to be seen. Certainly from the amount of time devoted to this kind of scientific thinking in the course of one day, one would not expect substantial changes without more of this type of training either in science itself or in other areas of the curriculum.

A second factor is that the Shockley program emphasizes intellectual processes rather than content. The ESCP and IPS programs also have this emphasis. In each program the process approach is somewhat "alien" to conventional practices and both students and teachers must undergo substantial modifications in their viewpoint as to what constitutes "science" in order to profit maximally from these new programs. The extent to which this character of the program attenuates its effect is unknown, but it is not implausible that some attenuation occurs. However, it must be admitted that under conditions where the attenuation would be most likely, an effect favoring Shockley training was obtained; and under conditions where it was least likely, no effects were produced.

Third, the changes in attitude in teachers and students hopefully would be long-term. The question of whether this program produces long-term effects has not been answered by these studies.

In conclusion, it seems that some questions have been answered substantially. The training does not produce obvious and massive intellectual growth within a short period of time. It does not appear to produce effects outside of the domain in which the training has occurred. One must suspend judgment on this point since the differences between the Shockley procedures and others is so marked. But one can be optimistic about attitudinal changes, changes in perception of the nature of science, and changes in how one feels about problem solving. These kinds of changes are themselves important educational outcomes and, as such, should not be minimized.

Chapter 6

RECOMMENDATIONS FOR FURTHER RESEARCH

The current interest in the field of education on the development of rational individuals, and in the field of science teaching on the processes of science, suggests the importance of studies on thinking. An analysis of the experimental and intuitive data from the Shockley-Stanford project suggests the need for further study in several categories.

In the following series of recommendations the first six reflect the viewpoint of the project investigators in education, and the remaining four reflect the approach of the engineering member of the study. This explains the slight overlapping in subject matter for future studies and also serves to emphasize the generally positive aspects of the Shockley Science Education Project.

1. The complex clusters of skills involved in problem solving probably require an extended period of time to develop to a high level of competence. What the critical period of time is, was not answered in the present study.

2. The success of any thinking or logical process rests heavily, as Dr. Shockley has pointed out, upon familiarity with the phenomena and the background of relevant concepts possessed by the learner. What is the "critical mass" of information that is needed before one is able to use logical processes effectively? To what extent is this influenced by genetic ability? by education? by motivation? by a combination of factors?

3. (a) It has been shown that the success of a new teaching program in science is dependent upon the extent to which the teacher understands the rationale and can translate it into teaching strategies. To learn a "thinking pattern" and to perform the associated exercises correctly is frequently not sufficient to assure that the rationale has been internalized or that the exercises are any more than rotely acquired. An unknown factor in this study is the extent to which teachers truly understood the rationale of the program. Further study along this line should include an analysis of teacher behavior in the classroom and the compatibility of his performance with the rationale of the program.

   (b) The same general conditions are also true for students. When a new program is introduced the "ground rules" are changed and the "payoff" is not like that he has been used to. In this instance the payoff is success in thinking through a problem situation and deriving a principle. It appears that considerable time needs to be devoted to this phase of teaching until the student thoroughly understands what is expected and the reasons behind these expectations.

4. The success of students on certain aspects of the Rational Reasoning Test leads one to suspect that there may be a closer relationship, and a greater ease of transfer, on certain training problems than on others. Further study along this line needs to be made.

5. There appears to be great personal satisfaction in "being able to see through" a problem. The extent to which this empirical reaction serves as a means of reinforcement in learning logical processes and in problem solving is in need of further study.

6. The games and puzzles are a unique feature of this project, and observations during the course of the study suggest two areas of study that would seem to be useful:

   a. What is the advantage of having students working together or teaching each other these game and puzzle activities?

   b. It was observed that the competitive games and puzzles were particularly interesting to pupils from a "disadvantaged" area, leading to the speculation that self-esteem--and as a result motivation for learning--may be influenced by the competitiveness of the situation itself. Further exploration of this area might produce significant results.

7. One of the impressive features noted by Professors Shockley and Gong, who both came in close personal contact with the teachers, was a very obvious change in teacher attitude and competence in dealing with difficult analytic problems. No measures were made of this change, which in some cases appeared to be almost a qualitative difference in intellectual attitude and competence. This observation leads to the recommendation that a similar program involving, for example, a seminar with teachers should be undertaken with pre- and post-tests on the teachers themselves.

8. One of the phenomena encountered in connection with the program is largely of an anecdotal nature which suggests a significant line of research for evaluating improvement in rational reasoning ability. This effect is known as the "McDonald Laugh" or the Schramm Anti-Laugh. This phenomenon has been encountered by many people under many circumstances but has apparently not previously been recognized and formally described. What it consists of is the emotional reaction of the student when he encounters a logical structure that has previously eluded him. This response may be vigorous: the individual may either be amused, possibly in an embarrassed way, or delighted with the elegance of a structure, or so embarrassed by his failure to see it that his chagrin is pronounced.

This observation suggests a line of research which might be carried out to determine whether or not familiarity with logical structure patterns has developed to such a point that it produces emotional reactions when the student encounters these patterns. Such a test procedure might be developed by using some emotion-detecting device such as the polygraph that is used in lie detectors. Measurements on this device would then be carried out in connection with problem solving on the part of the student or during the time when the student was presented to the problem in an anecdotal fashion so that the logical conclusion came as a surprise to him. It is possible that the degree to which appreciation of logical patterns was imparted to the student might then be measurable on the polygraph and that this measurement might reveal significant information both about the effectiveness of imparting these logical structure patterns and about the basic ability of the student to be influenced by such patterns. This is the well-known "Ah-ha" effect found in psychological literature.

9. Another area in which it is considered that further research in connection with this program might be worthwhile has to do with the setting up of situations (as discussed in Section ID) in which students help teach each other. The games and puzzles procedures of the program lend themselves particularly well to this type of activity; and now that these have been further developed, a program in which further efforts were made to have students teach students in a controlled experiment in comparison with teacher-dominated control groups would appear to be worthwhile and important.

10. Still another area has to do with the "Knowledge is Power" aspect of the program. Again an anecdotal situation indicates that the competitive game aspects may have a significant effect upon disadvantaged children by (1) increasing their interest in learning to use their minds, and (2) raising their self-esteem through a competitive advantage in respect to their contemporaries.

INDEX TO SEPARATE APPENDIX

The 10 instructional booklets described in Chapter 2 and the new test instruments described in Section 4A are presented in their entirety as a separate volume to this final report. This separate appendix is indexed as follows:

Teaching Units Developed

1. Take 1 or 3 Game
2. Two Coin Problem
3. Two King Problem
4. Odd-Evenness in Nature: The Mirror Problem
5. The Checkerboard Puzzle
6. Center of Gravity
7. Moments
8. Test Your Understanding: CG and Moments
9. Potential Energy
10. Competitive Games: Two Pile and Take One Through Five

Tests Developed

1. Nature of Science Inventory - Form X-2, and Problem-Solving Inventory - Form Y
2. Rational Reasoning Test Form Y-1
3. Rational Reasoning Test Form W-1
4. Rational Reasoning Test Form Z